moving dots have been used for global motion perception assessment based on OKN responses.

SUMMARY OF THE INVENTION

In one broad aspect the invention consists in a method for stimulus and eye tracking, useful for the determination of the presence or strength of optokinetic nystagmus (OKN), which comprises:

- providing a visual stimulus effective to elicit OKN in front of the eye(s) of a subject by:
    - displaying against a background on a display and varying in visibility (as perceived by the subject) of at least one visual stimulus element moving across the display, or
    - displaying against a background a series of at least one visual stimulus element moving across the display so that a later displayed element moving across the display has different visibility (as perceived by the subject) relative to an earlier displayed element moving across the display,
    - the moving visual stimulus element or elements comprising a centre and a contrasting perimeter, the perimeter darker than the background and the centre lighter than the background and/or the perimeter lighter than the background and the centre darker than the background,
- recording video of the subjects eye(s) viewing the stimulus, and
- image processing the video to detect for OKN.

In one broad aspect the invention consists in an eye tracking system which comprises:

- a display arranged to display against a background:
    - at least one visual stimulus element, and vary the visibility thereof (as perceived by the subject), or
    - a series of at least one visual stimulus elements so that a later displayed element has different visibility (as perceived by the subject) relative to an earlier displayed element,
    - the visual stimulus element or elements comprising a centre and a contrasting perimeter, the perimeter darker than the background and the centre lighter than the background and/or the perimeter lighter than the background and the centre darker than the background,
- a camera arranged to record video of the subjects eye(s) viewing the stimulus, and
- an image processing system arranged to image process the video to detect the presence or strength of OKN.

In at least some embodiments varying the visibility of the visual stimulus element(s) comprises causing the visual stimulus element(s) to vanish (as perceived by the subject).

In at least some embodiments at least one visual stimulus element progressively vanishes (as perceived by the subject) on the display, or a later displayed element progressively vanishes (as perceived by the subject) relative to an earlier displayed element. In other embodiments varying the visibility of the visual stimulus element(s) comprises causing the visual stimulus element(s) to increase in visibility or appear (as perceived by the subject). In at least some embodiments at least one visual stimulus element progressively appears (as perceived by the subject) on the display, or a later displayed element progressively appears (as perceived by the subject) relative to an earlier displayed element.

For example varying the visibility of the visual stimulus element(s) or causing the visual stimulus element(s) to vanish may comprise reducing or increasing intensity (optionally including luminescent intensity), contrast (optionally including luminance contrast, chromatic contrast, motion contrast or orientation contrast), size and/or width (spatial frequency) of the visual stimulus element(s) or visual stimulus element boundaries.

In at least some embodiments a spatial content, speed, temporal frequency (flicker), chromatic properties (colour), disparity (3D depth), and rotation or rotational speed of the stimulus (if not rotationally symmetric) of the visual stimulus are varied.

In at least some embodiments the visual stimulus element or elements comprise a perimeter that is darker than a background and a centre that is lighter than the background, and/or a perimeter that is lighter than a background and a centre that is darker than the background. In at least some embodiments the visual stimulus element or elements comprise:

- a perimeter having a perimeter boundary that is darker than a background and a centre having a centre boundary that is lighter than the background, and/or
- a perimeter having a perimeter boundary that is lighter than a background and a centre having a centre boundary that is darker than the background.

In these embodiments, when the boundary lines cannot be resolved they merge together and become indistinguishable from the background. The visual stimulus element is perceived by the subject to vanish or disappear. Alternatively the boundary lines emerge and become distinguishable from the background. The visual stimulus element is perceived by the subject to appear.

In at least some embodiments the visual stimulus elements comprise circle(s) and/or ellipse(s).

In at least some embodiments the visual stimulus element(s) may move across the display and progressively vanish as they move across the display. In other

same direction for example from left to right, at the same or different speeds. Alternatively stimulus elements may move in different directions, and for example stimulus elements in an upper row may move across the display in one direction while stimulus elements in another row such as a lower row may move across the display in an opposite direction, at the same or different speeds. Stimulus elements may move from top to bottom of a display or vice versa. Stimulus elements may move diagonally across a display.

In a preferred form a vanishing optotype stimulus (visual stimulus element) comprises a perimeter that is darker than a background and a centre that is lighter than the background, and/or a perimeter that is lighter than a background and a centre that is darker than the background. In at least some embodiments the perimeter has an outer diameter or transverse dimension OD = αSW and thickness SW(α-1)/2 wherein SW is a diameter or transverse dimension of the centre and α is in the range 1-5 or more preferably 1 to 3.

A single vanishing disk stimulus element is shown by itself in Figure 3(a), and as part of an array in Figure 3(b) where it has been over-layed on a background. Figure 4 on the right hand side shows a vanishing stimulus element – as it vanishes reduces from 3.0 to 0. Figure 4 on the right hand side shows the vanishing stimulus element with α initially = 3.0, and then also at α = 2.0 and at α = 1.4.

The diameter or transverse dimension (the stimulus element may not be circular) SW may be regarded as the stroke-width of the stimulus element, specified in logMAR. This centre is surrounded by a perimeter or annulus which may be of constant thickness SW(α-1)/2, the stated formulae resulting from considering the central disk (width diameter SW) as overlaying the surrounding outer disk with diameter OD = αSW. The stimulus shown to the observer may be an array of such vanishing disks that cover the screen. The horizontal and/or vertical centre-to-centre spacing DS may be for example in the range 1 to 10 or more preferably 2 to 6 x the diameter or transverse dimension SW of the stimulus element, and the entire array drifts across the screen either leftwards or rightwards at a constant angular velocity for the entirety of the duration of a presentation.

In the examples shown in Figure 4 the initial or starting intensity SI of the centre is lower than that PI of the perimeter. The background intensity BI is between that of the perimeter and centre. For example BI may initially be about half of PI. Another

possible intensity profile is shown in Figure 4. As stated, in the three specific examples on the right hand side of Figure 4 α = 1.4, α = 2.0 and α = 3.0. In each case SI = 1.0, PI =0.45, and BI = 0.5. Where the perimeter is darker than the centre then for example PI may be between 0 to 0.5 of maximum intensity, SI between 0.5 to 1.0 of maximum intensity, and BI between 0.4 to 0.6 and typically about 0.5 of maximum intensity. Example ratios are SI/PI/BI of 0.9/0.45/0.5 and 0.75/0.45/0.5.

Alternatively instead of reducing or increasing in intensity or luminescent intensity, the contrasting perimeter may reduce in size and/or vanish or increase in size and appear (as perceived by the subject), as the circle(s) and/or ellipse(s) move across the display. The centre may remain substantially constant. Figure 3(a) shows a single circle or ellipse stimulus of an embodiment of the invention and Figure 3(b) shows an embodiment of a visual stimulus which comprises multiple circles and/or ellipses (visual stimulus elements) moving across the display in series from left to right or vice versa and in upper and lower rows. In one option some stimulus elements, such as stimulus elements in one row, may be caused to vanish or appear as they move while other stimulus elements, such as stimulus elements in another row, do not. This may enable assessment of a direction that OKN goes in, which may allow for the assessment of discrimination between visible stimuli – known as the just noticeable difference.

Figure 5 shows an embodiment of a visual stimulus which comprises multiple disk visual stimulus elements moving across a display in series from left to right in three rows, at three stroke-width stimulus levels, with the stroke-width decreasing from high to low (going from left to right). The aim of visual acuity testing is to determine the stroke-width value at which the observer cannot detect the presence of the presented field.

Figure 6 shows the expected perception of the observer possessing refractive error. In this case the perception of the stimuli presented in Figure 5 is now degraded in all cases. The perception by the observer is that the disks are visible but progressively more difficult to detect as the stroke-width parameter is reduced. In this example, it is seen that the field of disks has vanished completely at the smallest stroke-width parameter setting (the right-most panel of Figure 5). The threshold of detectability has been passed, and the subject's OKN response has disappeared (as indicated by "OKN absent" on the right-most panel of Figure 6). In both figures it is noted that the field of disks would be moving in a fashion (for example, drifting continuously either

Some embodiments further comprise comparing the average velocity information to known optokinetic nystagmus velocity information to make a determination of the health of an eye in response to the stimulus.

The system may be implemented as a dedicated instrument, in portable or handheld device having both a camera and a computational power, such as a smart phone, tablet or laptop device, for example. Figure 7 shows an overview of the components of the system including the camera 60 for recording the eye footage, a screen 70 for displaying the stimulus and a computational device 80.

Image processing and OKN detection

Video processing for OKN detection or assessment may comprise extracting eye velocity and/or displacement information from video, using for example an optical flow algorithm or a point tracking algorithm. The video footage is used to make an estimate of the velocity and/or displacement, of an eye as a subject watches the visual stimulus, such as determining a velocity and/or displacement estimate of pixels inside the coarse determination of a limbal region and/or pupil region of an eye by application of an image processing algorithm known as optical flow and/or point tracking. In preferred embodiments, a Lucas-Kanade optical flow algorithm and/or a Kanade-Lucas-Tomasi (KLT) or other point tracking algorithm may be used. The velocity and/or displacement estimate provided by the optical flow and/or point tracking algorithm is an average of the pixel velocities and/or displacement in the coarsely determined limbal and/or pupil region. Heuristic analysis and/or template matching algorithm may be applied to the displacement and/or velocity estimate to determine the presence and direction of OKN. The velocity and/or displacement estimate information may also be manually compared to healthy eye velocity and/or displacement information, and in particular the velocity threshold at which OKN is no longer present, or drops below a predetermined threshold for OKN strength, to make a comparative judgement of the function of the eye and/or the visual pathway. The velocity and/or displacement estimation may also be used to track the direction of a person's gaze. The direction of the gaze may be used to judge behavioural characteristics of a person including information such as what visual stimulus gains their attention. In some embodiments the optical flow and/or KLT algorithm is applied to determine pixel velocity and/or displacement information between consecutive frames of a length of video footage corresponding to several reset events.

The method of determining OKN according to various embodiments is conducted according to the following steps. A video sequence containing footage of the eye is recorded while the eye watches a stimulus. In some embodiments, the video footage is reduced to grey scale to reduce computation complexity. An optical flow and/or point tracking image processing algorithm is applied to the video footage to determine pixel velocity and/or displacement information from sequential frames. The velocity and/or displacement information is determined from a limited region of the eye and that region is the limbus and/or pupil and/or limbal edge portion of the eye. The region is a coarse estimate of the limbal and/or pupil region of the eye determined by an edge detection and/or thresholding algorithm. The image processing algorithm outputs optical flow and/or point tracking information represented by pixel velocity and/or displacement information in the determined limbus and/or pupil region of the eye over two consecutive frames in the video footage. The pixel velocity and/or displacement information, including the speed, displacement and direction, can be directly assessed to determine the presence and direction of OKN.

One example of the steps of the process is shown in Figure 8 where the transformation of two consecutive image frames into an estimate of pixel velocity is shown. In a first step 10, consecutive video frames I(t) and I(t + 1) are taken from high definition colour video footage and reduced to gray scale. In a second step 20, a coarse determination of the limbal region of the eye is determined by an edge detection process applied to the video footage to determine an edge map. The edge map represents a determination of the location of the limbus portion of the eye and therefore the area of the video footage from which optical flow information is to be determined. The edge map does not need to be precisely determined for the optical flow information to be useful. The process is robust to variation in the limbal edge maps obtained throughout frames in the video footage. The edge detection is ideally performed by application of a Prewitt operator with hysteresis thresholding. However, those skilled in the art will recognise other edge detection strategies or operators could be used to determine the limbal region. Connected regions under a certain weight and regions connected to the image border are removed. In a third step 30, which may be processed concurrently or before the second step 20, an optical flow estimation process determines pixel velocity information from spatial and temporal changes in pixel intensity. As shown in Figure 1(c), a limbal region should exhibit a velocity spike during a rapid resetting event of an eye (saccade) and smooth or constant velocity changes during other periods when a stimulus is being observed.

Figure 2 shows the optical flow process in greater detail. Figure 2(a) shows an image or single frame of a piece of video footage showing an eye. Figure 2(b) shows a number of vectors indicating the magnitude and direction of pixel travel between consecutive frames. Figure 2(c) is a graph of the average velocity of the pixel vectors of Figure 2(b) for a number of consecutive frames.

In the fourth step 40 of Figure 8, the limbal region information provided by the edge detection process 20 is combined with the pixel velocity information provided by the optical flow process 30 to produce a masked velocity field. The masked velocity field represents velocity information only within the detected limbal region. In a fifth step 50, the velocity information from the masked velocity field is averaged to produce a velocity value for a given pair of consecutive frames in the video footage. The process of Figure 8 is performed on as many consecutive frames in the video footage as desired such that a graph of velocity is provided as a function of time. The graph can then be analysed to determine OKN information.

Further information is given in international patent application publication WO2014/168492 the entire contents of which are incorporated herein by reference.

Another example of the steps of the process is shown in Figure 9 where the transformation of two consecutive image frames into an estimate of pixel displacement and velocity is shown. In a first step 10, consecutive video frames I(t) and I(t + 1) are taken from high definition colour and/or infrared video footage and reduced to gray scale. In a second step 20, a coarse determination of the pupil region and pupil centre of the eye is determined by a thresholding algorithm and morphological operations applied to the video frame. The KLT algorithm estimates the new location of pupil centre in video frame I(t+1) based on changes in pixel intensity. By extracting pupil centre in two consecutive frames, displacement and velocity signal of pupil/eye can be determined.

These techniques are substantially robust against the error induced by head movements seen in normal adult fixations, eye blinks, reflections and other error inducing factors. Further, these techniques may be combined with head stabilisation for use with young children or subjects who would not tolerate head mounted equipment. These techniques are therefore video-oculography techniques readily applicable to infants or young children who would otherwise be unable to be assessed. These techniques may be implemented with standard 'off the shelf' video equipment

sensitivity, ADHD, dizziness/balance, fatigue, cognitive function, neurological disorder, multiple sclerosis, child development disorder, anything that interferes with the visual pathways of the brain, mental health disorder, anxiety, depression, sensory processing disorder, or neurodegenerative disorder such as Parkinson's and/or Alzheimer's Disease.

Experimental

We tested the ability of a vanishing disk based stimulus to estimate visual acuity as determined by an ETDRS visual acuity chart. We found a better test-retest reliability for the testing based on OKN than that of the visual acuity chart. We found a robust correlation (R^2 = 0.9) between the ETDRS and OKN visual acuity data, across a cohort of adults with uncorrected refractive errors (in the right eye only). The line of best fit after recalibration yielded "fitted" minimum sensitivity of the test (*c*) which was -0.01 logMAR, whilst the agreement with the visual acuity (*m*) was 1.04 logMAR by OKN method/ logMAR by VA chart. A second experiment was conducted in which blurring was used to test the range from 0.0 to 0.5 logMAR. Two stimulus parameter settings were tested, giving good linear fitting results of R^2 =0.76 and 0.86 respectively. The fitted line coefficients were (*m* = 0.62, *c* = 0.05) and (*m* = 0.50, *c* = 0.21). The thinner stimulus had the best fitted minimum sensitivity and improved agreement with the visual acuity chart overall, whilst the thicker stimulus had the worst sensitivity (*c* = 0.21) and the lowest agreement (*m* = 0.50) overall. Overall we found a linear relationship between visual acuity using OKN and ETDRS, and furthermore we were able to manipulate the optokinetic response, by only adjusting the alpha parameter.

Experiment One: Visual acuity testing with refractive error

Method

Participants: Healthy participants (N = 18, Average age = 29 ±6 years) were recruited through the School of Optometry and Vision Science.

Baseline visual acuity by ETDRS VA chart: Because it was expected that the eyes performance for a particular individual would be correlated, only data for right eyes was included for analysis in this experiment. Participants were instructed to stand 3 metres from the ETDRS-type VA chart (AT-20P Medmont Acuity Tester, Medmont Pty Ltd, Australia) and to read letters starting from larger letters at higher logMAR levels (maximum size logMAR 1.3) down to smaller letters at lower logMAR levels (minimum size logMAR -0.3) in 0.1 logMAR decrements (5 letters per logMAR

CLAIMS

1. A method for stimulus and eye tracking, useful for the determination of the presence or strength of optokinetic nystagmus (OKN), which comprises:

- providing a visual stimulus effective to elicit OKN in front of the eye(s) of a subject by:
  - displaying against a background on a display and varying in visibility (as perceived by the subject) at least one visual stimulus element moving across the display, or
  - displaying against a background a series of at least one visual stimulus element moving across the display so that a later displayed element moving across the display has different visibility (as perceived by the subject) relative to an earlier displayed element moving across the display,
  - the moving visual stimulus element or elements comprising a centre and a contrasting perimeter, the perimeter darker than the background and the centre lighter than the background and/or the perimeter lighter than the background and the centre darker than the background,
- recording video of the subject's eye(s) viewing the stimulus, and
- image processing the video to detect for OKN.

2. A method according to claim 1 wherein varying the visibility of the visual stimulus element(s) comprises causing the visual stimulus element(s) to vanish or appear (as perceived by the subject).

3. A method according to claim 1 or claim 2 wherein varying the visibility of the visual stimulus element(s) or causing the visual stimulus element(s) to vanish or appear comprises reducing or increasing intensity, contrast, size and/or width of the visual stimulus element(s) or visual stimulus element boundaries.

4. A method according to any one of claims 1 to 3 wherein the visual stimulus element or elements comprise:

- a perimeter having a perimeter boundary that is darker than a background and a centre having a centre boundary that is lighter than the background, and/or

- a perimeter having a perimeter boundary that is lighter than a background and a centre having a centre boundary that is darker than the background.

5. A method according to claim 4 wherein the perimeter has an outer diameter or transverse dimension OD = αSW and thickness SW(α-1)/2 where SW is a diameter or transverse dimension of the centre and α is in the range 1 to 5.

6. A method according to either claim 4 or claim 5 wherein varying the visibility of the visual stimulus element(s) comprises reducing or increasing an intensity, contrast, or a size and/or width, of the perimeter relative to the centre of the visual stimulus element(s) or of the perimeter relative to a background.

7. A method according to any one of claims 1 to 6 wherein a spatial content, speed, temporal frequency, chromatic properties, disparity, and rotation or rotational speed of the stimulus (if not rotationally symmetric) of the visual stimulus varies.

8. A method according to any one of claims 1 to 7 wherein the visual stimulus element(s) move across the display with varying visibility as they move across the display.

9. A method according to any one of claims 1 to 8 wherein a later displayed element moving across the display has lower or higher visibility relative to an earlier displayed element moving across the display.

10. A method according to any one of claims 1 to 9 wherein the perimeter of the visual stimulus element or elements is darker than the background and the centre, an intensity of the centre of the visual stimulus element or elements is between 0.5 to 1.0 of a maximum intensity, and an intensity of the perimeter of the visual stimulus element or elements is between 0.4 to 0.6 of a maximum intensity.

11. An eye tracking system which comprises:

- a display arranged to display against a background:
    - at least one visual stimulus element, and vary the visibility thereof (as perceived by the subject), or
    - a series of at least one visual stimulus elements so that a later displayed element has different visibility (as perceived by the subject) relative to an earlier displayed element,

- the visual stimulus element or elements comprising a centre and a contrasting perimeter, the perimeter darker than the background and the centre lighter than the background and/or the perimeter lighter than the background and the centre darker than the background,
- a camera arranged to record video of the subject's eye(s) viewing the stimulus, and
- an image processing system arranged to image process the video to detect the presence or strength of OKN.

12. A system according to claim 11 arranged to vary the visibility of the visual stimulus element(s) by causing the visual stimulus element(s) to vanish or appear (as perceived by the subject).

13. A system according to claim 11 or claim 12 arranged to vary the visibility of the visual stimulus element(s) or cause the visual stimulus element(s) to vanish or appear by reducing or increasing intensity, contrast, size and/or width of the visual stimulus element(s) or visual stimulus element boundaries.

14. A system according to any one of claims 11 to 13 wherein the visual stimulus element or elements comprise:

- a perimeter having a perimeter boundary that is darker than a background and a centre having a centre boundary that is lighter than the background, and/or
- a perimeter having a perimeter boundary that is lighter than a background and a centre having a centre boundary that is darker than the background.

15. A system according to claim 14 wherein the perimeter has an outer diameter or transverse dimension OD = αSW and thickness SW(α-1)/2 where SW is a diameter or transverse dimension of the centre and α is in the range 1 to 5.

16. A system according to any one of claims 12 to 15 arranged to vary the visibility of the visual stimulus element(s) by reducing or increasing an intensity, contrast, or a size and/or width, of the perimeter relative to the centre of the visual stimulus element(s) or of the perimeter relative to a background.

17. A system according to any one of claims 11 to 16 arranged to vary a spatial content, speed, temporal frequency, chromatic properties, disparity, and rotation or rotational speed of the stimulus of the visual stimulus.

18. A system according to any one of claims 11 to 17 arranged to move the visual stimulus element(s) across the display with varying visibility as they move across the display.

19. A system according to any one of claims 11 to 18 arranged to move a later displayed element moving across the display with lower or higher visibility relative to an earlier displayed element moved across the display.

20. A system according to any one of claims 11 to 19 wherein the visual stimulus element or elements comprise a perimeter that is darker than a background and a centre, an intensity of the centre of the visual stimulus element or elements is between 0.5 to 1.0 of a maximum intensity, an intensity of the perimeter of the visual stimulus element or elements is between 0.4 to 0.6 of a maximum intensity.