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Y. A. W. de Kort, W. A. IJsselsteijn, I. M. L. C. Vogels,
M. P. J. Aarts, A. D. Tenner, & K. C. H. J. Smolders (Eds.)

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Volume Editors

Yvonne de Kort, PhD
Wijnand IJsselsteijn, PhD
Karin Smolders, MSc
Eindhoven University of Technology
IE&IS, Human-Technology Interaction
PO Box 513, 5600 MB Eindhoven, The Netherlands
E-mail: {y.a.w.d.kort, w.a.ijsselsteijn, k.c.h.j.smolders}@tue.nl

Ingrid Vogels, PhD
Visual Experiences Group
Philips Research
High Tech Campus 34, WB 3.029
5656 AE Eindhoven, The Netherlands
E-mail: ingrid.m.vogels@philips.com

Mariëlle Aarts, MSc
Eindhoven University of Technology
Department of Architecture Building and Planning
PO Box 513, VRT 6.34
5600 MB Eindhoven, The Netherlands
E-mail: M.P.J.Aarts@tue.nl

Ariadne Tenner, PhD
Independent consultant
Veldhoven, The Netherlands
E-mail: ariadne.tenner@onsmail.nl

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Reflections on the Eyelid: Experiencing Structured Light through Closed Eyes

Adar Pelah
Department of Electronics
University of York
Heslington, York YO10 5DD
ap23@york.ac.uk
Also at:
Department of Engineering,
University of Cambridge,
Trumpington Street,
Cambridge CB2 1PZ.

Siyuan Liu
St John's College
University of Cambridge
Cambridge CB2 1PT

Howard Hock
Department of Psychology
Florida Atlantic University
777 Glades Road
Boca Raton, FL 33431-0991

Mathew Gilbert
Department of Electronics
University of York
Heslington, York YO10 5DD

Philip Jepson
Department of Electronics
University of York
Heslington, York YO10 5DD

ABSTRACT
It is generally taken that closure of the eyes for periods longer than a blink blocks visual perception due to the presumed diffusion of image structure by the eyelids. Although as much as 14.5% of the light incident at the eyelid may reach the retina, a capacity to visually perceive meaningful structure has not previously been proposed. We report on visual experiments through the closed eyelid, demonstrating the presence of both spatial and temporal sensitivity. By Rayleigh's criterion, we found a mean spatial resolution of 21° for the closed eye (N=17), in comparison with optimal open eye resolution of approximately 0.008°. In addition, we found that motion direction discrimination was qualitatively comparable to performance with an open eye that was perceptually matched with the closed eye for blur and brightness (N=8). Confidence in making closed eye observations was significantly lower than with open eyes, and subjects' mean blur and brightness matching using the open eye overestimated (based on previous measurements of transmission through the eyelid) the attenuation of light in the closed eye by more than 50 times. A further observation indicates that colour naming can also be made accurately through closed eyes. Applications of the findings are considered in the context of how light and pattern may be experienced on the *dark side* of human vision.

Keywords
Closed eyes, eyelid, motion sensitivity, direction discrimination, Rayleigh's criterion, colour naming

INTRODUCTION
The present investigation challenges the widely-held assumption that the world cannot be perceived visually when the eyes are closed. Closing the eyes attenuates significantly the characteristics of the retinal image affecting the consequent reception by conscious (i.e. perceptual, cognitive, cortical) and non-conscious (i.e. circadian, reflexive, subcortical) neural mechanisms. The factors leading to the attenuation of the retinal image when the eyes are shut may be broken down into the spectral filtering and diffusion applied by the skin of the eyelid prior to the light reaching the retina. We examine experimentally the extent of the spatial and temporal attenuation. We consider whether, under controlled lighting and display conditions, perceptual processing may still take place through closed eyes, and if thus, what are the implications, and what advantage can be made for lighting and well being applications.

Spectral Filtering
Sensitivity when the eyes are closed is heavily reduced, especially at short and medium wavelengths, with most of the uniform light reaching the retina radiating in the 'red' region of the spectrum [2, 9, 13, 14]. Subjective observation confirms readily the band-pass nature of the eyelid filter at long wavelengths: for example, looking at an intense, broad spectral light source (such as the sun) normally produces an appearance through closed eyes of a broadly homogenous field of light with a reddish hue.

The observation favouring a red coloured filtering effect by the eyelid has also been confirmed by formal investigation. Ando & Kripke's [2] threshold measurements for the detection of light passing through the eyelid indicated that there was 94% attenuation for monochromatic red light, compared with 99% for blue and green light. Physical measurements find spectral characteristics for the eyelid that are similar to other blood-bearing biological tissue. Robinson et al [13] delivered monochromatic light through a fibre-optic that was mounted onto a contact lens, with the output detected on the outside skin of the eyelid using a photodiode. Their data from 5 adult subjects indicate that the eyelid acts as a predominantly red-pass filter with mean transmissions at 700nm and with as much as 14.5% of the light transmitted across the skin of the eyelid. Similar measurements with 9 preterm neonates indicated the transmission of 21.4% if the light.

Diffusion

In addition to heavy spectral filtering, a second attenuation factor present when closing the eyes is the diffusion of the spatial structure of the image incident at the eyelid, blurring the retinal image prior to photoreception. The extent of the blur is assumed implicitly in the literature, and commonly by lay people, to be total and therefore the main cause for blocking visual perception with closed eyes. It has never been measured, to our knowledge, probably for this reason Our first objective, therefore, is to estimate the blur due to the eyelid by measuring spatial resolution to determine if it is instead finite in extent and quantifiable under controlled conditions.

Spatio-temporal Structure

Whether or not meaningful visual perception can take place with closed eyes can be determined by measuring the psychophysical performance of human observers in spatial and temporal visual tasks. Comparing the results to appropriately matched open eye equivalents would indicate whether the underlying mechanisms are the same for open- and shut-eye vision. Spatial resolution is often measured in optical studies by the Rayleigh criterion [16], which is defined as the minimal retinal angle subtended for which the separation between two point sources can be resolved. The minimal resolvable angle thus measured defines the line-spread function (the inverse of the modulation transfer function), which is readily converted to spatial resolution (see, for example, Fig. 1).

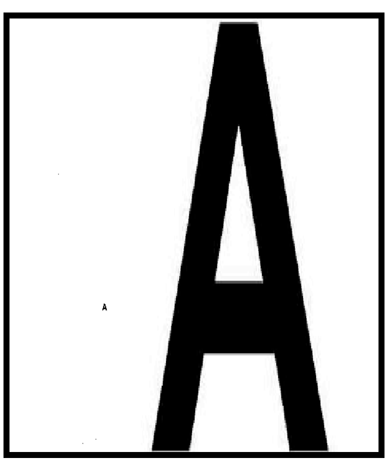

Figure 1. Illustration comparing the Snellen optometric chart visual acuity for an open eye (barely visible ‘A’, left) to the theoretical Snellen acuity of a closed eye through the eyelid (large ‘A’, right). The relative letter sizes are derived from the ‘worst’ Snellen acuity (open eye), and ‘best’ Snellen acuity (closed eye) calculated from the mean Rayleigh resolution (see Experiment 1).

Our second objective is to assess whether vision with closed eyes can include functional perceptual properties in the temporal domain. Motivated by the evolutionary need for predator avoidance, perhaps the simplest task to examine for temporal sensitivity across the eyelids would be direction discrimination during motion. With closed eyes under bright illumination - conceptually, for instance, for predator avoidance, a shadow cast on the eyelid would firstly need to be detected, and secondly, its direction of motion would need to be discriminated (e.g. in order to take the correct evasive action). This was addressed experimentally by testing our subjects’ ability to detect motion direction for the brief presentation of a vertical bar drifting to the left or right, measured separately for the shut and open eye, with brightness and blur perceptually matched beforehand.

Our final objective, if visual perception can be shown to take place through closed eyes, is to consider what use can be made of the reported visual property, especially for the benefit of human health and wellness. We consider in our discussion categories of eye closure and discuss possible directions for applying the finding within each of them.

METHODS

Experimental methods are described below for the overall setup, and separately for the spatial resolution (Experiment 1), perceptual matching (Experiment 2) and direction discrimination (Experiment 3) experiments.

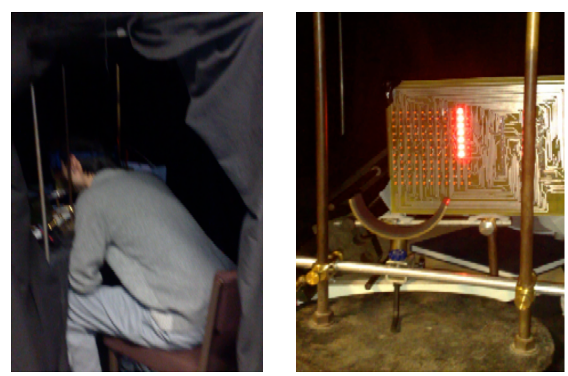

Figure 2. The experimental setup. Left: A subject is seated in the experimental booth; during experiments the curtain would be drawn for complete darkness. Right: The subject’s chin rest and stimulus display array. An illuminated vertical column of the red LEDs is shown. For Experiment 1, the viewing distance is changed by moving the display array along calibrated track (partly visible on the lower left).

Experimental Setup

Physiological optics generally neglects the optical properties of the eyelid (or treats it as opaque), though it is rightly the first stage of the visual pathway when the eyes are closed. The eyelid can be modeled as a spectral filter, attenuating light differentially across the visible spectrum, placed in series with a diffuser that blurs the image. Spectral attenuation by the eyelid is highest at the blue and green regions of the spectrum, with most of the energy at the photoreceptors remaining in the red (due to the optical properties of skin and blood) [2, 9, 13, 14]. As our objective for obtaining resolution thresholds was to measure the blur that includes the degrading effects of the eyelid we maximised effective transmission in the apparatus by restricting stimuli to light in the red region of the spectrum. We used a custom, computer controlled stimulus grid designed and built in-house consisting of 9 rows by 9 columns of bright, red LEDs spaced 1.0 cm apart along each of the vertical and horizontal axes of the grid (see Fig. 2, Right Panel).

The spectral peak of each LED in the display array was 635 nm with a bandwidth of 45nm at half height. Experimental observation was done monocularly, with one eye closed and the other patched to full darkness at a given trial, using a chin-rest for stability and a Maxwellian view that allowed subjects to sit at comfortably close distances to the stimulus grid centred at the eye (see Left and Right Panels of Fig. 2). LEDs that were lit were displayed at equal, high brightness levels. The total luminance flux per area was determined by measuring, with a photometer, the luminance of a single LED (269 cd/m^2), multiplying this by the area of an LED (circular, 3mm diameter) to get the amount of luminous flux that the LED would contribute to the display. The single LED's value is then multiplied by the number of LEDs illuminated in a given stimulus configuration to obtain the total flux, which is then divided by the area encompassed by the illuminated cluster. In Experiment 1, the 4 x 7 LED display (Fig. 3, Left Panel) has a luminance of 30.0 cd/m^2, while the respective luminance values for the display in Experiments 2 and 3 (see Fig. 4) is 33.3 cd/m^2.

Informed consent was obtained from subjects prior to their participation; all subjects were between the ages of 20-23 years and had normal or corrected to normal vision through contact lenses. Subjects first dark adapted for at least 20 min prior to the commencement of trials and were allowed at least 10 min of practice to become familiar with the nature of the apparatus and the experiments. Measurements for spatial resolution were made using the method of limits (the viewing distance was manually manipulated by the experimenter in order to vary the size of the retinal angle subtended by the test stimulus), while those for directional discrimination were done using a 2-alternative, forced choice (2AFC) paradigm by randomly varying the motion direction of the stimulus. Subject responses were made verbally in Experiment 1 and 2, and by button presses corresponding to 'left' or 'right' direction with a hand-held keyboard in Experiment 3.

Experiment 1 – Rayleigh resolution

Spatial resolution thresholds were determined on the basis of the Rayleigh criterion [14], defined as the minimum resolvable detail, as limited by factors such as diffraction, blur and noise. Functionally, the Rayleigh criterion is measured as the smallest retinal angle at which a gap is resolved between two adjacent point sources. To enable better performance through brighter stimuli, we used columns of LEDs rather than point sources, thus obtaining resolution based on the alternative 1-D optical line-spread function rather than the 2-D point-spread function [see 5}. The Rayleigh criterion was thus taken as the maximal distance between the eyelid and the array at which a 2.0 cm gap between two vertical LED columns was resolved and discriminated from 1.0 cm gap (see Fig. 3). The two frames were presented alternately for a 1.0 s duration each interleaved by a dark frame of the same duration. Viewing distance was used to estimate thresholds for resolving the fixed stimulus gap, owing to the limitations in the range of resolutions possible with our custom built bright LED display apparatus. A confound with stimulus luminance therefore occurs owing to light attenuation with increasing distance; superior resolution values are likely to be achieved using more advanced displays with higher luminance values that are held constant, while varying stimulus resolution directly. 17 subjects participated in this experiment and each subject's testing session required approximately 30 min.

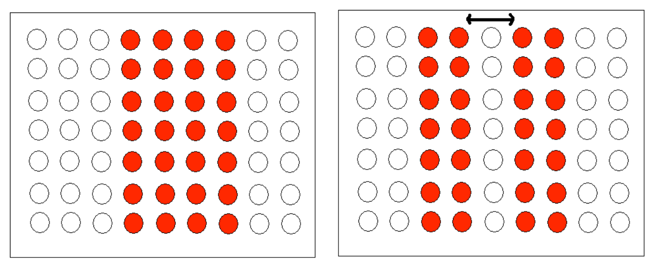

Figure 3. The display frames used for measuring Rayleigh criterion for Experiment 1. The two frames were alternated repeatedly, interleaved at 1 Hz by a blank frame (not shown). The physical gap between adjacent columns was 1cm (which was not detectable at the range of viewing distances used), thus the gap to be resolved in the second frame was 2cm wide (see arrow, right frame). The subjects were required to correctly identify and verbally confirm the visibility of the gap, with viewing distance manually adjusted to the largest distance, and therefore the smallest retinal angle, for which subjects correctly named the frame containing the gap.

Experiment 2 – Perceptual matching

Quantitatively comparing open and closed eye vision required that the stimulus properties of the former be perceptually matched to that of the latter. Subjects were asked to wear a custom-made facemask to which layers of neutral density (ND) filters and sheets of tracing paper could be attached in front of each eye's view, for light attenuation and, in addition, blur. Each ND filter attenuated light intensity by 75.0%, while tracing paper attenuated light intensity by 97.0% per sheet. We then presented subjects with a bright, steady LED array stimulus consisting of three vertical columns, asking subjects to match the percept seen in the closed left eye with that of the open right eye, by covering each eye alternately while observing the stimulus with the other. We added and removed filters and sheets of tracing paper to the open eye's view until the subject reported no difference between the percepts for both eyes.

A subject's settings therefore consisted of a finite number of ND filters and tracing paper sheets, from which the viewed luminance may be computed for the open eye as the perceptual match to the closed eye. If settings were based on veridical luminance perception, as measured for light transmission through the eyelid by other studies [2, 13], then we would expect filter settings for the open eye's view that achieve between 5% and 14.5% light transmission.

13 subjects participated in this experiment and each subject's testing session required approximately 15 min. One additional subject reported difficulty doing the matches and also produced extraordinary results. These data were therefore excluded from the sample as an outlier.

Experiment 3 – Direction discrimination

Directional discrimination thresholds were determined as the percentage of correct responses ('left' or 'right') for three vertical columns of illuminating LEDs drifting in the horizontal direction over a sequence of three 400 ms frames (2.5 Hz), as illustrated in Fig. 4. The viewing distance used to present the stimuli was 2.0 cm, resulting in a temporal drift velocity of ±70 °/s. Stimulus brightness was varied by placing the appropriate number of layers of ND filters in front of the LED array.

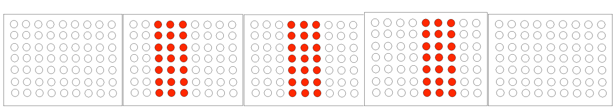

Figure 4. The display frames used for discriminating direction of drift in Experiment 3. The frames were presented in sequence at a rate of 2.5 Hz from left to right, as above; the illustrated sequence corresponds to rightward motion. Blank frames appear as shown at the start and end of each presented sequence.

RESULTS

Experiment 1 – Rayleigh resolution

Spatial resolution thresholds were obtained from one-dimensional Rayleigh criterion judgments. Expressed in degrees of visual angle at the nodal point of the eye, the mean (± SD) Rayleigh resolution was 20.95° (±8.44°). The viewing distance values across all subjects are normally distributed, as shown in Fig. 5. The mean Rayleigh resolution may be compared to the equivalent resolution for open eyed vision. Under optimal conditions, the diffraction-limited, optical resolution [e.g. 5] has been shown to match that of the neural pathways [6] to a value of approximately 0.0083°.

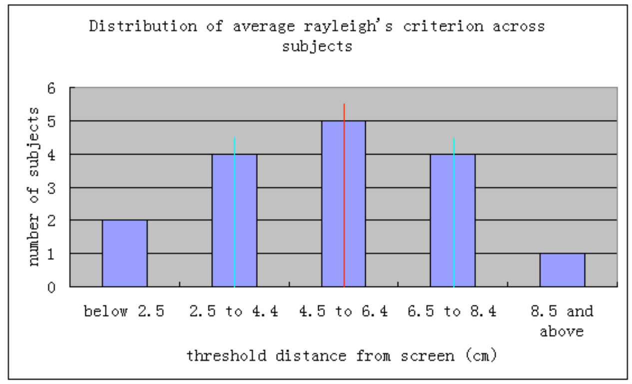

Figure 5. The distribution of viewing distance for spatial resolution measured according to Rayleigh's criterion in Experiment 1. The mean, shown at the vertical red line, is 5.409cm, which is equivalent to 20.95°±8.44° of visual angle subtended at the nodal point of the eye. The standard deviation, shown by the blue lines, is ± 1.96,. N=17.

Experiment 2 – Perceptual matching

Perceptual matching was obtained, as explained in Methods, between the percept from a bright light as viewed by an open eye through filters to that seen in the closed eye. The filter settings (also used for Experiment 3) show a considerable mean ((± SD) over-estimation of the amount of brightness attenuation taking place across the closed eyelid of 0.09% (± 0.21) transmission (i.e. 99.01% attenuation); this may be compared with published estimates of approximately 5% transmission (i.e. 95% attenuation) for similar perceptual measurements [2]. This is more than a 50-fold over-estimation. In addition, there are large differences in subjects' individual perceptual settings. (see Table 1, column 3).

Sub ID	Matched filters (ND & TP)	Transmission (%)
1	4 & 3	1.05E-05
2	2 & 2	5.63E-03
3	2 & 2	5.63E-03
4	2 & 1	1.88E-01
5	4 & 2	3.52E-04
6	1 & 8	1.64E-11
7	1 & 4	2.03E-05
8	2 & 6	4.56E-09
9	2 & 2	5.63E-03
10	1 & 1	7.50E-01
11	2 & 2	5.63E-03

12	2 & 2	5.63E-03
13	2 & 1	1.88E-01

Table 1. Subjects' individual filter settings in Experiment 2 selected for the open eye to match the perceived appearance of a bright light source seen through the eyelids in the closed eye. The first number in the middle column indicates the number of neutral density filters, each with 75% light transmission. The second number in the middle column indicates the number of sheets of tracing paper, each with a 97% light transmission. The mean transmission percentage (± 1 SD) through the matched open eye filter for all subjects was 0.09% (± 0.21), a large overestimation of the attenuation (compared to earlier reports), or equivalently, an underestimation of brightness through the eyelid.

Experiment 3 – Direction discrimination

Directional discrimination thresholds for 8 subjects for open and closed eye conditions are shown in Fig. 6. Results show clearly that motion direction can be discriminated through a closed eyelid. This appears to take place in a qualitatively similar manner as a function of stimulus luminance as it does through a perceptually matched open eye. However, it is also clear that performance in the open eye remains superior to that of the closed eye by approximately 15-20% under the conditions in the present experimental setup. The quantitative difference is seen despite the filtering applied individually for each subject (see Table 1, and Experiment 2) to match the percepts in the two conditions. As indicated earlier, the matching made the open eye's view darker than would have been expected from previous measurements [2, 13]. So the difference in direction discrimination between closed and open eyes may have been under-estimated in this experiment.

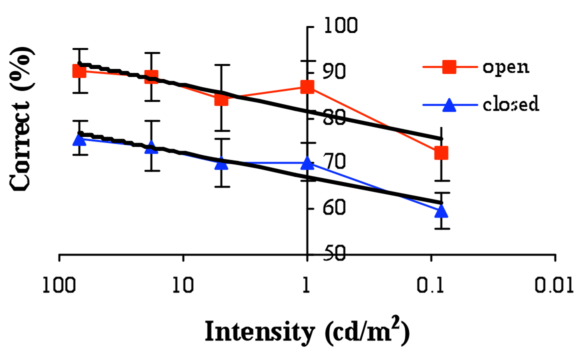

Figure 6. Mean subject performance (% correct) in discriminating the direction of motion monocularly through an open or closed eyelid. In the open eye condition subjects viewed the stimulus through tracing paper and a series of neutral density filters, selected individually as a perceptual brightness and blur match to their closed eye percept. Discrimination is easier through an open eye despite the matched percept and probable overestimation of attenuation in the perceptual matching (see Table 1), though performance appears qualitatively similar in the two conditions. Errors bars are shown as ± standard errors of the mean. N=8.

A Colour Naming Observation

The spectral filtering of the eyelid is well known and although colour perception behind the closed eyelid has not explored, the filtration is thought largely to impoverish the retinal image of chromatic information except in the red. The experiments we report make use of a band limited red LED display panel in order to maximize the brightness at the most effective spectral range, namely in the red. However, we also make the following observation. We presented single, bright (uncalibrated) LED key-chain type flashlights in red, green, white and blue, applied in random order at the surface of the eyelid to one closed eye (the other eye was patched). The five subjects tested, with 10 or more presentations of each colour, were able to name the colour to near complete accuracy. Thus, human perception of colour, and thus the presence of cone vision, is not precluded when the eyes are closed.

DISCUSSION

The investigation began with questioning the commonplace presumption that active visual perception is extinguished when the eyes are shut. Indeed, in basic psychophysical, neurophysiological, and applied vision research, a closed eye condition is often used as the controlled 'no-vision' condition. There undoubtedly is extensive attenuation of visual information through closed eyes. However, casual observation (through introspection) of a small uniform light source through closed eyes has motivated us to consider whether structural spatiotemporal image information may be detected and perceived under certain circumstances; and if this is so, whether such shut-eye visual processing may serve to benefit novel applications in medicine, lighting and imaging research, as well as improve our understanding of visual processing.

Our preliminary survey of visual capacity through closed eyes of two visual spatiotemporal parameters, spatial resolution and directional discrimination, demonstrate that spatiotemporal structure can be perceived in visual images seen through the closed eyelids. The novelty of making conscious observations with closed eyes, and probably the reduced control of eye position sense [1], leads subjects to report a reduced confidence in their judgments. When questioned at the end of experimental runs, subjects reported mean (± SD) confidence[1] in their direction discrimination of 7.63 (±1.97), with the eye open, compared with only 4.76 (±2.48) with it closed, a reduction in confidence of 38%. The reduced confidence cannot

[1] Confidence scale 0 to 10; 0 = 'no confidence', 10 = 'complete confidence.'

explain the underestimation of perceived brightness through the eyelid (see Table 1), as uncertainty would more likely lead to a large variance but not necessarily an order of magnitude or two of underestimation in perceived brightness of the closed-eye.

Subject accuracy, particularly for direction discrimination, is nevertheless good. Percentage correct for the most visibly (i.e. brightest) stimulus is only 14% lower for the closed eye (see Fig. 6). A likely reason for the inferior direction discrimination of the closed eye is the absence of position information due to the severe loss in spatial resolution through the eyelid. Indeed, the discrimination of motion direction despite such severely impaired spatial resolution, provides a clear instance of objectless motion perception [15], as also observed for blindsight patients [3]. There is no indication, however, that performance would not continue to improve with further increases in image brightness.

Spatial resolution, as measured by the Rayleigh criterion, is extremely poor compared with open-eye vision (see Fig. 1), yet surprisingly good compared with what might be expected, namely, an absence of any resolvable detail when the eyes are shut. The poor resolution is due to the blur and brightness reduction of the eyelid caused by diffusion. The expected dominance of lower-resolution, rod-mediated vision operating at the eyelid-attenuated light levels following dark adaptation would not be expected to be a significant factor, as the rods perform poorly for red light. In addition, we found that colour perception, the hallmark of cone-mediated vision, can take place with closed eyes. Our estimates are therefore conservative, given the greater resolving power of the cones, and we believe that significantly higher resolutions than reported here are likely to be detected with improved conditions.

Extended periods of eye closure are normally associated with sleep, when only relatively large and abrupt changes in ambient light level seem to affect behaviour (e.g. by waking or stirring the sleeper). On the other hand, sufficiently slow, gradual changes in ambient level are not likely to be perceived consciously through closed eyes (or even open eyes), although some light transmission through the closed eyelid would presumably be advantageous to assist circadian training as dawn approaches. For structured light, it may be important, for ecological reasons of predator avoidance for instance, to collect at least the edges and direction of movement of an approaching shadow cast on the eyelids. It is therefore not unreasonable on first principles to expect that eyelids should be designed through evolution to allow for transmission of light and some images.

It is promising and attractive to learn that a richer and more complex appreciation of the environment can be obtained from light incident on the closed lids of the eyes. While the underlying mechanisms for visual perception during eye closure are not fully understood, our finding that structured spatiotemporal light is perceptible behind the eyelid could have applications in medicine, architecture, education or entertainment.

In relation to our final objective for this study, we therefore consider that people close their eyes within three categories of experience, and suggest possible thinking on applications within each. Naturally, each will present its own challenges and unanswered questions on implementation are outside the scope of this paper.

1) Reflex and maintenance, as with natural blinks for moistening the eye surface, and protection from bright light or physical objects nearing the eye. The prospect that useful visual information can be delivered to the eyes during brief periods of closure could be applied to high-speed physical and informational activities, for instance in sports, battle, or other time-critical safety monitoring scenarios, such as car racing or air-traffic control.

2) Communications and emotions, as in facial expressions, or responses to enjoyment, fear etc. Within this category, one could envisage additional modalities of communicative information conveyed visually during eye closure, for instance, to enhance or modify the emotional state or convey more subjective information during these intervals during video telephony (e.g. Skype) type communications.

The third category to consider is 3) Sleep, relaxation and related states of longer duration eye closure. During eye closure brain activity is distributed differently, and eye movement velocities are greater, as reported by. Marx et al [8]. Interestingly, they also argue from brain imaging (fMRI) results concerning the presence of two distinct mental states: an ‘exteroceptive’ state when the eyes are open, characterized by attention and oculomotor activity, and an ‘interoceptive’ state during extended periods of eye closure, dominated by imagination and multisensory activity. Perhaps applying custom-structured light displays during eye closure to awake individuals could cross such normal boundaries, by instigating a mixture of perceptual processes and unusual experiential effects?

Differences are found for certain medical conditions that may support this view. For example, the eye movement patterns of schizophrenics are different when their eyes are open compared to when their eyes are closed [10]. Applications in this category may thus include visual stimulation during eye closure for schizophrenic patients, for epilepsy patients [7], who demonstrate abnormal brain patterns during eye closure [4], fro coma patients, who have abnormal sleep-awake patterns, and for other patients with ‘disorders of consciousness’ (i.e. coma, vegetative state and minimally conscious state) [11, 12]. It is conceivable that stimulation during eye closure periods for such patients could stimulate different brain areas and trigger alternative pathways to facilitate diagnosis or treatment.

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