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Visual discomfort, neural inefficiency and the cortical haemodynamic response

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Abstract

We show that visual perception of an image becomes uncomfortable when the image evokes a large haemodynamic response. The aversion of gaze that results therefore has the potential to reduce the use of energy by the brain. We consider four features of images from nature, and show that unless the image has each feature, it is rated as relatively uncomfortable to view. The cortical haemodynamic response evoked is then larger than when the image is more natural and more comfortable. There are large differences between observers as regards discomfort from images. The cortical haemodynamic response is larger in observers who experience discomfort. The relationship between visual discomfort and the amplitude of the cortical haemodynamic response therefore applies both across stimuli and across observers. We propose that the unnatural visual images encountered in urban life result in inefficient neural processing and are detrimental to health.

Keywords: *eye strain, asthenopia, near infrared spectroscopy, sparse coding, sensory sensitivity, environmental design, migraine, autism spectrum disorders*

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1. Introduction

The human visual system evolved to process scenes from nature and is optimised to do so efficiently with "sparse coding," meaning that few neurons are active at any one time [1, 2] Here, we consider four characteristics of natural images. First, the Fourier amplitude spectrum of the luminance is approximately proportional to the reciprocal of the spatial frequency; second, the distribution of contours shows a preponderance of those with vertical or horizontal orientation; third, colour contrast between nearby parts of the image is small; finally, there is little flickering light.

With respect to each of these four characteristics, we will show that when images are unnatural (such as those in **Figure 1**) they are also uncomfortable. They evoke a relatively large haemodynamic response, suggesting inefficient neural processing.

2. 1/f Fourier amplitude spectrum

The sparse coding of visual neurons takes advantage of the redundant statistical properties of natural scenes e.g. [1, 3–7]). Natural scenes show a scale invariance that gives rise to a spatial frequency amplitude spectrum characterised by the function $1/f^k$, where f is the spatial frequency and k is approximately 1 [1, 8–10]. Fernandez and Wilkins [11] asked observers to rate discomfort incurred from a wide variety of images including works of art, photographs, and filtered visual noise. The images were judged to be uncomfortable when the slope of the Fourier amplitude spectrum departed from 1/f. Discomfort was greatest when the departure from 1/f was due to a relative excess of energy at mid-spatial frequencies, to which the visual system is most sensitive. Juricevic et al. [12] asked observers to rate levels of discomfort from colour images generated from noise or random overlapping rectangles ("Mondrians"). Those with amplitude spectra with a 1/f slope were rated as more comfortable than those with steeper or shallower slopes. Penacchio and Wilkins [13] obtained discomfort ratings for a wide variety of images, and fitted a cone with a 1/f slope to the two-dimensional Fourier amplitude spectra. The goodness of fit explained more than a quarter of the variance in judgements of discomfort.

Le et al. [14] used Penacchio and Wilkins' model to analyse images of building frontages. The model not only accounted for judgements of discomfort, but also predicted the size of the cortical haemodynamic response to the images. There was a larger response to those images that were unnatural and uncomfortable. The response was measured using near-infrared spectroscopy (NIRS). Changes in infrared reflectance in superficial regions of the cortex were measured from optodes on the scalp. The response was maximal in posterior head regions, suggesting involvement of the visual cortex; subcortical involvement could not be measured, and no particular region of interest was applicable, because the haemodynamic response measured by NIRS is aggregated over many different superficial cortical regions. In a study by Isherwood et al. [15], apparently conflicting results were obtained. The functional magnetic resonance imaging (fMRI) blood oxygenation level dependent (BOLD) signal was measured from visual areas V1, V2

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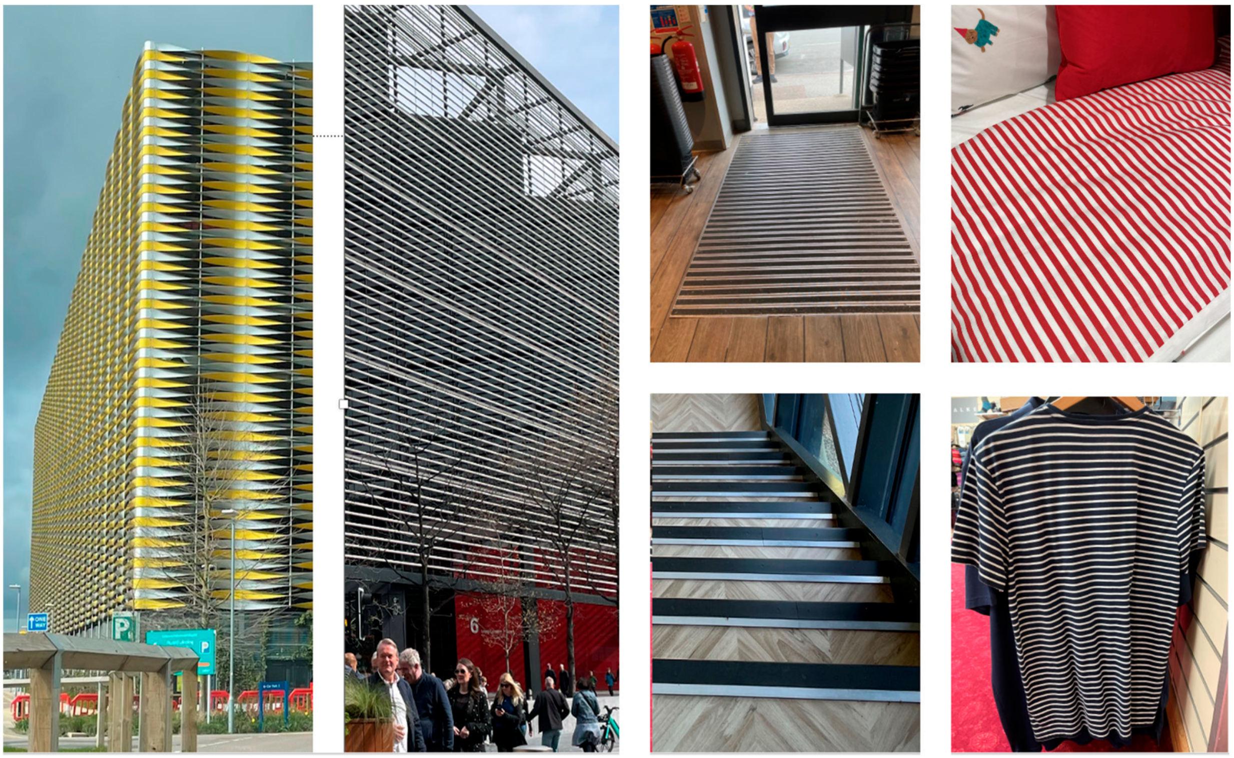

Figure 1 • Examples of repetitive patterns on building exteriors, interiors, bedding, and clothing.

and V3. The response within this local region of interest was possible because of the greater localisation of the BOLD response. The BOLD response within this region was larger rather than smaller when the amplitude spectrum had a slope of 1/f. The size of the overall haemodynamic response (unrestricted by region of interest) was not measured. Discomfort was not assessed.

In summary, images with unnatural Fourier amplitude spectra are often uncomfortable to view, and, when uncomfortable, they cause a large aggregated haemodynamic response.

3. Contour orientation

Using filtered visual noise, Ogawa and Motoyoshi [16] studied the effects of orientation bandwidth on discomfort. They showed that images with an uneven orientation spectrum (as occurs in nature) were the more comfortable. There is a preponderance of contours in vertical or horizontal orientations in scenes from nature [17]. This is often used to explain the "oblique effect" [18], whereby gratings in oblique orientation can be seen less readily than gratings in vertical and horizontal orientations. Gratings with oblique orientation are rated as being less comfortable than those in cardinal orientation [19] and they elicit a NIRS response that is more than 20% larger in peak amplitude [20]. If fMRI BOLD is used and measurement is confined to V1 [21] or the parahippocampal place area [22], the response is larger with cardinal orientations. Once again, the BOLD response within local regions of interest differed from the aggregated haemodynamic response. Although NIRS and BOLD responses are generally correlated they can differ if the response areas are dissimilar [23].

In summary, gratings with a relatively unnatural orientation and orientation spectra are uncomfortable and give a large aggregated cortical haemodynamic response.

4. Colour contrast

Images from nature usually have a moderate *local* colour contrast, with a difference in CIE UCS chromaticity between neighbouring pixels averaging less than 0.01 [24]. Paintings usually have a larger local colour contrast [24], notwithstanding the differences in other statistics [25]. When observers are asked to rate discomfort from works of art, those works with a larger average local CIE UCS chromaticity difference give the greater discomfort [26]. Similarly, coloured square-wave gratings are rated as uncomfortable in proportion to the difference in chromaticity between the bars. The size of the cortical NIRS response to the gratings also increases with the difference in CIE UCS chromaticity, and is larger in posterior head regions [27]. Images of everyday objects in which the colour saturation is increased or decreased relative to the typical saturation are both rated as uncomfortable and give larger NIRS responses [28].

In summary, images with an unnaturally large or small local colour difference are uncomfortable and cause a relatively large aggregated cortical haemodynamic response.

5. Flicker

Flicker is rare in nature, occurring mainly when sunlight is interrupted by leaves or reflected from waves (the only natural visual stimulation documented as being responsible for photosensitive seizures [29]). Flicker is generally uncomfortable whenever it is experienced, whether from variation in luminance [30] or chrominance [31]. Patterson Gentile and Aguirre [32] examined the association between visual discomfort and the evoked potential in the primary visual cortex. They used flicker of different temporal frequencies that separately targeted the LMS, L-M, and S post-receptoral pathways. They found a simple linear relationship between discomfort and the amplitude of the evoked potential, regardless of the post-receptoral pathway. To date, no one appears to have repeated this experiment with haemodynamic response, but flicker is known to elicit large haemodynamic responses both in the retina [33] and in the cortex [34].

6. Implications

In all four of the above respects, visual stimuli that are rare in nature are uncomfortable and elicit a large cortical response in posterior head regions. This response is therefore distinct from the more anterior and subcortical responses typically associated with an emotion [35]. There is considerable evidence that visual neurons encode natural stimuli efficiently [36–38]. Perhaps the haemodynamic response is large when the neural computation is relatively inefficient. This viewpoint is suggested by the work of Picard et al. [39], who showed that as a task is learned, the amplitude of the evoked haemodynamic response decreases. This would also be consistent with the findings of Coggan et al. [40], who showed a large haemodynamic response to phase-scrambled grey-level images of everyday objects compared with the un-scrambled originals. Perhaps the association between discomfort and the size of the cortical response reflects not emotion, as such, but an inefficient neural computation—an inefficiency that occurs when unnatural or unlearned visual stimuli are processed. The discomfort may encourage aversion of gaze and thereby prevent excessive cortical metabolism and support homeostasis.

7. Differences between observers

The difference between individuals in susceptibility to discomfort is so large that some individuals find visual stimulation exciting that would, in others, result in discomfort and a headache. The striped paintings of the artist Bridget Riley are exciting for some and uncomfortable for others. Not only does the visual discomfort differ from one observer to another, so does the size of the haemodynamic response. In individuals with trypophobia, for example, the observation of clusters of small holes elicits aversion: mainly disgust. In a study by Le et al. [41], the cortical NIRS response to images of holes was nearly twice the amplitude of that observed with other images (There were also heart rate changes, although blood pressure was not measured). Again, the NIRS response was maximal in posterior head regions, consistent with involvement of the visual cortex. In observers with no trypophobia, there were no differences between images of holes and other images.

Individuals with migraine, who find patterns of stripes uncomfortable [42], have a large BOLD response in the visual cortex when such uncomfortable patterns are observed [43]. Even observers with no clinical condition, who experience discomfort from glare, show a larger haemodynamic response in visual areas [44].

8. Discomfort and the haemodynamic response

There is therefore a relationship between discomfort and the size of the cortical haemodynamic response in visual areas of the brain both across stimuli and across observers. Frontal regions are rarely implicated, which suggests that the discomfort is unlike emotional responses which typically have a subcortical and frontal predominance [45]; this is notwithstanding the fact that image content is sufficient to predict the category and valence of human emotion ratings [46]. The involvement of visual areas supports the neurological mechanisms of discomfort proposed by Wilkins et al. [47] who drew attention to the similarity between the stimuli that provoke discomfort and those that evoke seizures in patients with photosensitive epilepsy. Both discomfort and seizures may be manifestations of hyperneuronal responses to strong sensory stimulation.

9. Neurological differences

Patients with migraine are known to be particularly susceptible to strong sensory stimulation, and there is widespread convergent evidence that in migraine the brain is hyperexcitable [48]. The nature of the hyperexcitability can be inferred from (1) the comorbidity of epilepsy and migraine [49], (2) the use of antiepileptic medication in migraine prophylaxis [50]; (3) the effects of transcranial magnetic stimulation in the induction of phosphenes [51]; (4) the larger electrophysiological responses to sensory stimuli [52]; and (5) the perceptual distortion in response to strong sensory stimulation that occurs in both visual [42] and auditory [53, 54] modalities.

The sensory sensitivity in migraine also occurs variously in other conditions, most notably autism spectrum disorder [55], which also has a high co-morbidity with epilepsy [56]. The sensory sensitivity may reflect inefficient neural processing with an associated hyperneuronal response, as documented in migraine by Huang et al. [43]. Such a viewpoint is in line with a computational model of visual discomfort that demonstrates a reduction in the sparseness of neuronal activity in response to uncomfortable visual stimulation. It models the individual differences between observers as a variation in intracortical inhibition, with the balance shifting toward increased excitation over inhibition in individuals experiencing discomfort [26].

10. Conclusions

Scenes in the modern world differ from those in the natural environment in all four of the characteristics identified above. There are repetitive patterns on building exteriors—increasingly so, over the last century [57]. There are many stripes within building interiors, and on furnishings and clothes; see **Figure 1**. These patterns have Fourier luminance amplitude spectra that depart from 1/f. The saturation of colour is often greater than in nature, and the local colour contrast is far greater. The structure and colour of the patterns is therefore often uncomfortable, sometimes epileptogenic, and can affect gait [58]. It is not only the spatial and chromatic structure that is detrimental: temporal modulation is pervasive in artificial lighting, and it is known to be detrimental to health [59] (this modulation impairs reading speed even when the frequency is well above that at which flicker is perceived [60]). These features may help to explain some of the visual discomfort in urban life, and the greater susceptibility of certain patient groups; they may also help to explain the health benefits of exposure to the natural environment [61].

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