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Discomfort from urban scenes: Metabolic consequences

An T.D. Le[a], Jasmine Payne[a], Charlotte Clarke[a], Murphy A. Kelly[a], Francesca Prudenziati[a], Elise Armsby[a], Olivier Penacchio[b], Arnold J. Wilkins[a,*]

[a] Department of Psychology, University of Essex, United Kingdom
[b] School of Psychology and Neuroscience, University of St Andrews, United Kingdom

HIGHLIGHTS

- Certain statistical properties of images are responsible for visual discomfort.
- These properties are prevalent in images of the modern urban environment.
- The discomfort is associated with inefficient neural processing and a large metabolic demand.

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ABSTRACT

Scenes from nature share in common certain statistical properties. Images with these properties can be processed efficiently by the human brain. Patterns with unnatural statistical properties are uncomfortable to look at, and are processed inefficiently, according to computational models of the visual cortex. Consistent with such putative computational inefficiency, uncomfortable images have been demonstrated to elicit a large haemodynamic response in the visual cortex, particularly so in individuals who are predisposed to discomfort. In a succession of five small-scale studies, we show that these considerations may be important in the design of the modern urban environment. In two studies we show that images from the urban environment are uncomfortable to the extent that their statistical properties depart from those of scenes from nature. In a third study we measure the haemodynamic response to images of buildings computed as having unnatural or natural statistical properties, and show that in posterior brain regions the images with unnatural statistical properties (often judged uncomfortable) elicit a haemodynamic response that is larger than for images with more natural properties. In two further studies we show that judgments of discomfort from real scenes (both shrubbery and buildings) are similar to those from images of the scenes. We conclude that the unnatural scenes in the modern urban environment are sometimes uncomfortable and place excessive demands on the neural computation involved in vision, with consequences for brain metabolism, and possibly also for health.

1. Introduction

Scenes from nature have in common the characteristic that their gross aspects have a higher contrast than the fine detail. In mathematical terms, the Fourier amplitude spectrum decreases approximately as the reciprocal of the spatial frequency, i.e. approximately as 1/f (Field, 1987). The neural computation involved in sight is well-designed to take advantage of the 1/f characteristic (Field, 1987, 1994; Geisler, 2008).

Images with unnatural amplitude spectra are judged uncomfortable to look at (Fernandez & Wilkins, 2008; Juricevic, Land, Wilkins, & Webster, 2010; Penacchio & Wilkins, 2015). Such uncomfortable stimuli include the patterns of repetitive stripes that are commonplace in the modern urban environment. Computational models of the visual cortex by Hibbard and O'Hare (2014) and Penacchio, Otazu, Wilkins, and Harris (2015) suggest that such uncomfortable repetitive patterns render the firing of cortical neurons less "sparse", increasing the overall firing rate, with the potential of raising metabolism in consequence. Indeed, there is growing evidence for a raised metabolism in so far as uncomfortable stimuli trigger a strong haemodynamic response in the visual cortex. Huang, Cooper, Satana, Kaufman, and Cao (2003) used functional magnetic resonance imaging (fMRI) and measured the blood

* Corresponding author at: Department of Psychology, University of Essex, Colchester, CO43SQ, United Kingdom.
E-mail address: arnold@essex.ac.uk (A.J. Wilkins).

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oxygen level dependent (BOLD) response to achromatic gratings with a range of spatial frequencies. Contrast sensitivity is maximal at mid spatial frequencies and Huang et al. showed that high contrast gratings with mid spatial frequency (which are uncomfortable) gave the largest BOLD response. Haigh et al. (2013) used near infrared spectroscopy (NIRS) over the visual cortex and measured the haemodynamic response to coloured gratings. They found that coloured patterns of stripes gave a larger oxyhaemoglobin response if they had large differences in their component colours and were therefore uncomfortable to view.

Individuals differ in susceptibility to visual discomfort, and those individuals who are relatively susceptible show a larger haemodynamic response than those who are less so. This has been demonstrated in several studies involving patients with migraine but also those without. Thus Huang et al. (2003) demonstrated that patients with migraine report both discomfort and perceptual distortion when viewing gratings, and show an abnormally large BOLD response to such stimuli. Martín et al. (2011) compared 19 patients with migraine and 19 controls. Patients with migraine had a larger number of activated occipital voxels in response to lights than did controls. Cucchiara, Datta, Aguirre, Idoko, and Detre (2014) found that in migraine patients who experienced aura the number of symptoms of discomfort they reported by questionnaire correlated with the amplitude of the BOLD response to visual stimulation.

Although the studies reviewed in the above paragraph concerned patients with migraine, the relationship between discomfort and the size of the haemodynamic response occurs independently of this diagnosis. Thus, Alvarez-Linera et al. (2006) compared 20 photophobic patients with 20 controls who viewed a light source at various intensities. There was a direct relationship between stimulus intensity and the size of the BOLD response, and the response was larger in the photophobic individuals. Finally Bargary, Furlan, Raynham, Barbur, and Smith (2015) compared normal participants with high and low thresholds for discomfort glare while they identified the orientation of a Landolt C surrounded by peripheral sources of glare. The group that was sensitive to discomfort glare had a larger BOLD response localized at three discrete bilateral cortical locations: in the cunei, the lingual gyri and in the superior parietal lobules. In conclusion, both in terms of the visual stimuli and in terms of the people they affect, uncomfortable visual stimuli are associated with a large haemodynamic response.

The visual stimuli that are uncomfortable can be quantified mathematically. As shown by Fernandez and Wilkins (2008) and Penacchio and Wilkins (2015) they differ from natural images in having an excess contrast energy at mid-range spatial frequencies. The excess is relative to the energy expected on the basis of the reciprocal relationship between Fourier amplitude and spatial frequency typical of natural scenes (1/f). This characteristic is common in images from the urban environment, and it is this visual aspect of the environment that we explore with a series of five small-scale studies.

In the first two studies we show that photographs of certain buildings are consistently rated as uncomfortable and have an excess of energy at mid spatial frequencies relative to that expected from 1/f. (Spatial frequency refers here to the spatial repetition of contours on the retina and is therefore determined both by the size of the pattern and the distance from which it is viewed.) In a third study we show that observation of photographs with the statistical properties of unnatural images elicits a larger haemodynamic response than for other images, consistent with inefficient neural processing of unnatural and uncomfortable scenes. In two further studies we show that photographs of scenes are a good surrogate for the scenes themselves: the ratings observers make when looking at buildings or trees and shrubs correlate strongly with those made when observing photographs of the same scenes. The implication of these studies is that the design of the urban environment is such as to render the neural computation involved in vision more complex than it needs to be, with consequences for brain metabolism.

2. Studies 1 and 2: images of buildings

2.1. Procedure

Un-posed images of urban scenes were obtained by the simple expedient of standing at the side of a curb and aiming a camera across the street, angled so as to capture as much as possible of the facade of the building opposite from a distance of 5–12 m. A Sony α-390 DSLR camera (without a zoom) was used and the viewing angle of the camera was estimated from technical literature to be about 50°. The images were 960 pixels wide by 720 pixels high. Fig. 1 shows maps of the locations where the photographs were obtained, and Fig. 2 a sample of 25 such images.

The images were divided into two sets, one set for each study, each set consisting of 74 different photographs presented in random order on the 344 mm × 194 mm screen of an Acer Aspire 5734Z laptop computer from a viewing distance of 0.6 m, at which distance they were 18° high. Each image was presented until the observer had given a rating and they were encouraged to do so within 10 s. Observers were asked to rate the images on a 7-point Likert scale with 1 labelled "Very Comfortable" and 7 labelled "Very Uncomfortable".

2.2. Participants

Students at the University of Essex (12 males and 8 females aged 19–28) observed each of the images and gave a rating. Ten different students took part in Study 1 and 10 in Study 2, which was a replication.

2.3. Results

The images differed significantly with respect to the ratings they received (Study 1: $F(73, 657) = 3.00$, $p < 0.001$, $\eta2 = 0.25$; Study 2: $F(73, 657) = 6.39$, $p < 0.001$, $\eta2 = 0.41$). Cronbach's alpha between raters was 0.67 in Study 1 and 0.84 ("good") in Study 2.

2.4. Image analyses

The images were analysed using the algorithm described by Penacchio and Wilkins (2015). In their paper the studies are numbered 4 and 5. The algorithm measured how closely each image approximated a natural image in respect of the shape of the two-dimensional Fourier transform. In images from the natural world the amplitude of the spectrum decreases with increasing spatial frequency approximately as 1/f, so that on log–log coordinates the spectrum approximates a cone in shape, with a slope of −1. By varying the height of the cone, the algorithm obtained the best fit to the Fourier transform of each image and weighted the residuals by a contrast sensitivity function sourced from the literature, see Fig. 3. The monitors were not gamma-corrected, but such correction typically affected the slope of the spectral power distribution by less than 2%. The contrast sensitivity function had a peak at 7 cycles/degree and was reduced to 78% of its peak value at spatial frequencies of 3.5 and 14°, so variation in spatial frequency over a factor of about two, such as occurred with the variation in viewing angle was of little consequence. The sum of the weighted residuals correlated 0.60 with the ratings of discomfort from images used in Study 1 and 0.53 with those in Study 2. In other words, in both studies the algorithm explained more than 25% of the variance in the judgments of discomfort: images that best approximated the cone were rated as most comfortable. Altering the shape of the cone so

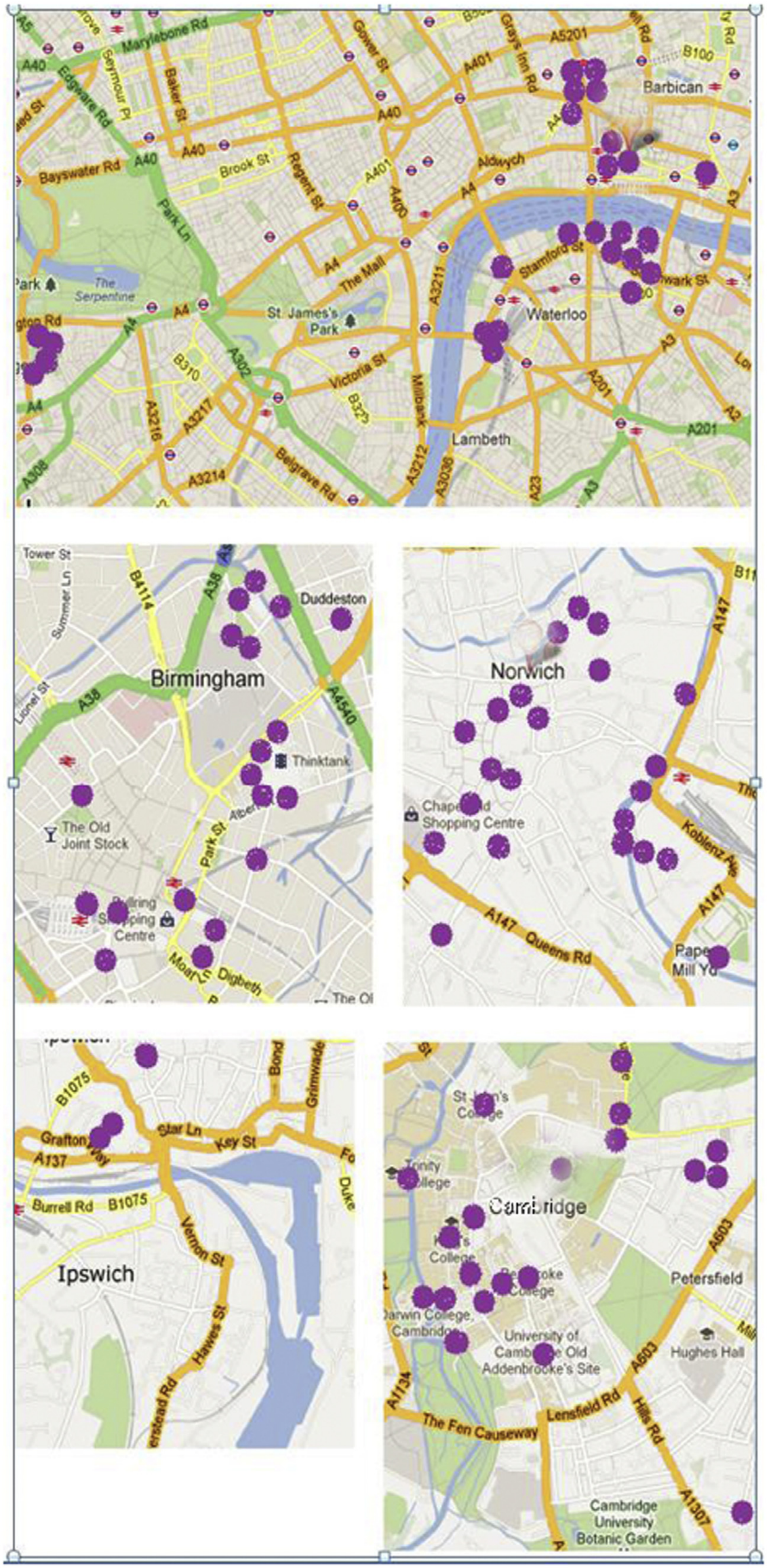

Fig. 1. Locations of buildings photographed. Top: London; Left centre: Birmingham; Right centre: Norwich; Bottom left: Ipswich; Bottom right: Cambridge.

Fig. 2. Thumbnails of the first 25 images presented in Study 1.

as to accommodate the orientation anisotropy in images made little difference to the ability of the model to predict discomfort, see Penacchio and Wilkins (2015).

In the next experiment participants observed a subset of the images of buildings while the cortical haemodynamic response was measured.

3. Study 3: haemodynamic response to images of buildings

3.1. Participants

Twenty-six volunteers from the general population and from the University of Essex served as participants. There were 4 males and 22 females, aged 18–53 (M = 26.4, SD = 11.6).

3.2. Stimuli and apparatus

Using the algorithm from Penacchio and Wilkins (2015), the residual score for each of the 148 images in Studies 1 and 2 was calculated and the images were divided about the median score into two groups, 10 images with high residuals (median rank 32.5, range 2–46) and 10 with low (median rank 108, range 71–125). As might be expected, the images with high residuals were largely those judged to be uncomfortable, and the images with low residuals were largely those judged comfortable. Nevertheless, the segregation of images was on the basis of their statistical structure and was therefore entirely objective.

The stimuli were presented on an UltraSharp 2408WFT 24" LCD monitor (60 Hz refresh rate) resolution 1920 × 1200. At the viewing distance of 0.7 m the height of the screen subtended 28.5°. At the 50% brightness level used, the white screen had a luminance of 101 cd m^{-2}.

3.3. NIRS procedure

The cortical haemodynamic responses to each image were measured using near infrared spectroscopy (NIRS). An 8-channel NIRS system was used (MK II; Artinis Medical Systems BV, Zetten, The Netherlands). The optode placement for the posterior channels included two receivers and six transmitters. The optodes for the receivers were placed 30 mm from either side of the midline 20 mm above the inion. For the left hemisphere, three transmitters were placed 35 mm from the receiver, above, to the left and obliquely at 45°. The symmetrically equivalent placement was used for the right hemisphere. The frontal channels included two receivers and two transmitters, in which the receivers covered positions FP1 and

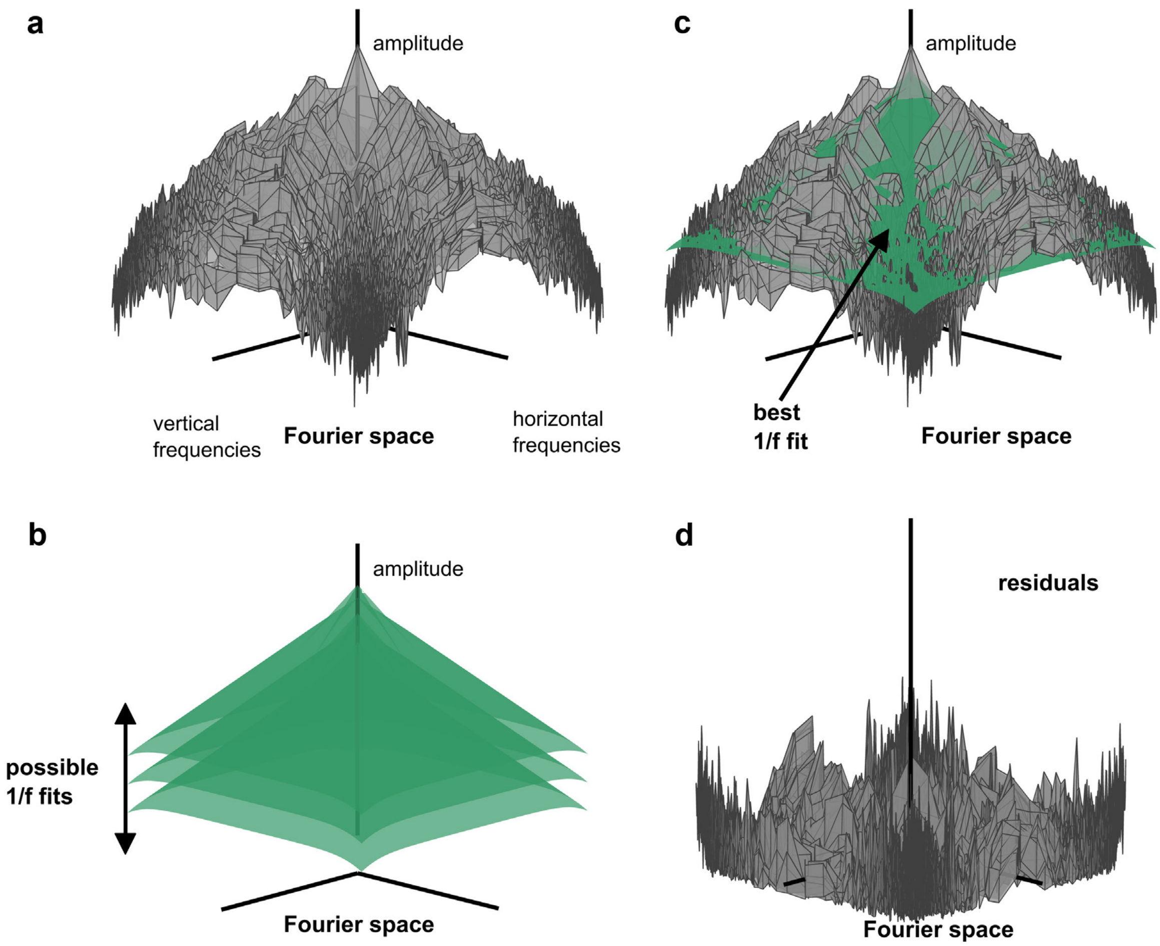

Fig. 3. Schematics of the computational metric of discomfort defined in Penacchio and Wilkins (2015). (a) Amplitude spectrum of one of the images in the study in log–log coordinates. The horizontal plane corresponds to the two-dimensional Fourier frequency domain and the vertical dimension to the (log) of the amplitude spectrum. (b) Set of circular regular 1/f cones (hence, with a slope of −1 in log–log coordinates) with different values for the gain. (c) Best fit amongst the set of circular regular cones in (b) to the amplitude spectrum shown in (a). (d) Residuals with respect to the best fit shown in (c).

FP2 of the 10–20 system of electrode placement. Both transmitters were placed 35 mm above their respective receiver. This was a close replication of the configurations used by Haigh et al. (2013).

The participants were asked simply to observe the images whilst keeping movement to a minimum. A PowerPoint slideshow presented each stimulus for 16 s in a fixed random order. Grey slides were used to separate the stimuli, and the inter-stimulus intervals ranged in duration at random between 27 and 36 s.

3.4. Data analysis

To calculate the oxygenated haemoglobin concentration, a differential path length factor (DPF) of 6.26 was used (Duncan et al., 1996). The raw signal was filtered with a running median of 31 samples to remove cardiac artefacts. The detrend function in MATLAB© was applied to remove any systematic drift in the signal. The deoxyhaemoglobin signals were small relative to the oxyhaemoglobin signals. They were negatively correlated, and significantly so ($r(23) = -0.57$, $p < 0.01$). For this reason only the oxyhaemoglobin responses were used in the subsequent analyses, following Haigh et al. (2013).

The haemodynamic response amplitude was measured in terms of the difference between the average of the signal during the last 10 s of stimulus presentation and the average 10 s before stimulus onset. Some channels did not record a good signal, often because hair obscured the optodes. Channels were therefore accepted for analysis only if the amplitude of the haemodynamic response was greater than the standard deviation of the signal during baseline, following Haigh et al. (2013).

3.5. Results

Twenty-five participants had at least one acceptable posterior channel (the average number of acceptable channels per participant was 4.4). The signal was stronger in posterior than frontal channels. Indeed in only five of the 25 participants were the data from frontal channels acceptable. In these five participants the overall amplitude for frontal channels ($M = 0.10\ \mu M$, $SD = 0.10$) was smaller than for posterior channels ($M = 0.35\ \mu M$, $SD = 0.27$), though not significantly so because of the small numbers, $t(4) = 2.06$, $p = 0.108$, $d = 1.3$.

The effects of the visual stimuli were analysed only for the posterior channels. The average amplitude for all such channels for each participant was obtained, separated by image category. Fig. 4 and Table 1 show, the residual score from the model by Penacchio and Wilkins (2015), the discomfort rating (from Studies 1 and 2), and the average amplitude of the oxyhaemoglobin response across participants.

A repeated-measures ANOVA with image category as main effect revealed that images with high residual scores induced a significantly larger haemodynamic response in the occipital areas, mean 0.40 μM (SD 0.29), compared to images with low residu-

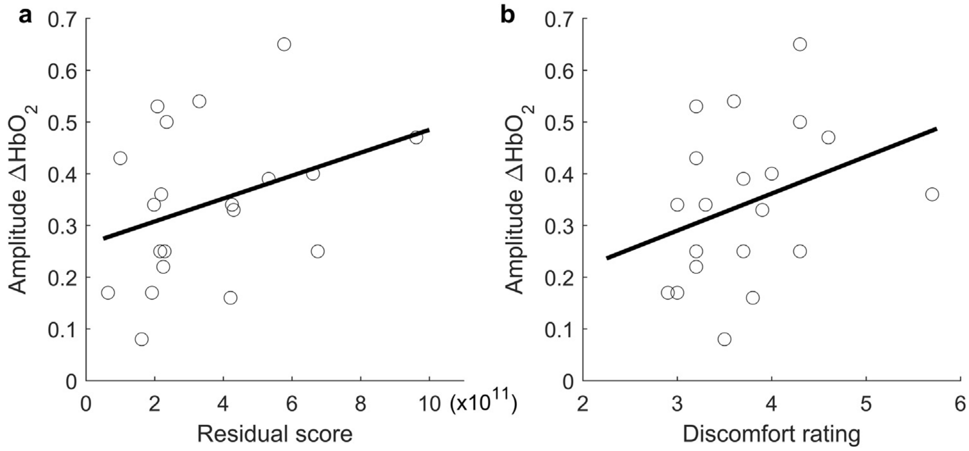

Fig. 4. (a) Scatter plot of the average amplitude of the oxyhaemoglobin response against the average residual score in Experiment 3. (b) Scatter plot of the average amplitude of the oxyhaemoglobin response against the average discomfort rating in Experiment 3. The black lines are illustrative and correspond to a linear least mean square fit, but note that the sampling of images was not random.

als, mean 0.28 μM (SD 0.17), $F(1, 24) = 4.73$, $p < 0.05$, MSE = 0.04, η2 = 0.17.

Fig. 5 shows the average oxyhaemoglobin response for images with high and images with low residual scores.

The above analysis separated images on the basis of residuals, however it was also important to separate images by discomfort rating. This is because some images might have high residuals yet low discomfort rating (and vice versa), and indeed when separating images by perceived discomfort (as assessed in Studies 1 and 2) four images were re-categorised (relative to the previous grouping). Again, a repeated-measures ANOVA with image category as main effect was conducted. The results showed revealed that uncomfortable images, mean 0.40 μM (SD = 0.28) induced a significantly larger haemodynamic response in the occipital areas compared to comfortable images mean 0.29 μM (SD = 0.19), $F(1, 24) = 5.40$, $p < 0.05$, MSE = 0.29, η2 = 0.18.

3.6. Interim discussion

Images of building frontages with a high residual score gave rise to a haemodynamic response of greater amplitude than did those images with a low score. When the images were separated according to discomfort rating, the greater amplitude was induced by uncomfortable images. These findings are consistent with other evidence reviewed earlier that, in general, uncomfortable visual stimuli are associated with a large haemodynamic response. The result demonstrates that images from the modern urban environment are sufficiently un-natural (and uncomfortable) to give a large haemodynamic response and that this response can be predicted quite objectively from the statistical properties of the image. A relatively large haemodynamic response is suggestive of a relatively large metabolic load in the occipital areas and therefore consistent with the behaviour of computational models of the visual cortex that indicate a less sparse and stronger neural response to stimuli that are uncomfortable. It has been suggested that the discomfort is a homeostatic response that acts to restore normal metabolism (Wilkins, 2015).

The fact that certain images of buildings are rated as uncomfortable and give rise to a large haemodynamic response suggests that there are aspects of the design of the modern urban environment that may be sub-optimal. Before such an inference can be made, however, it is necessary to demonstrate that photographs are an appropriate surrogate for real scenes in this respect. To do so, we asked observers to rate visual comfort from real scenes and, later, photographs of those scenes.

Table 1
Experiment 3: residual score, discomfort ratings and average amplitude of the oxyhaemoglobin response in order of stimulus presentation.

Image order	Residual score ($\times10^{11}$)	Discomfort ratings	Amplitude ΔHbO_2
1	4.21	3.8	0.16
2	9.62	4.6	0.47
3	2.19	5.7	0.36
4	3.30	3.6	0.54
5	1.98	3.3	0.34
6	2.29	3.7	0.25
7	6.61	4.0	0.40
8	1.62	3.5	0.08
9	0.64	3.0	0.17
10	4.30	3.9	0.33
11	1.00	3.2	0.43
12	2.08	3.2	0.53
13	6.75	4.3	0.25
14	4.25	3.0	0.34
15	2.35	4.3	0.50
16	5.32	3.7	0.39
17	2.16	3.2	0.25
18	2.25	3.2	0.22
19	5.77	4.3	0.65
20	1.92	2.9	0.17

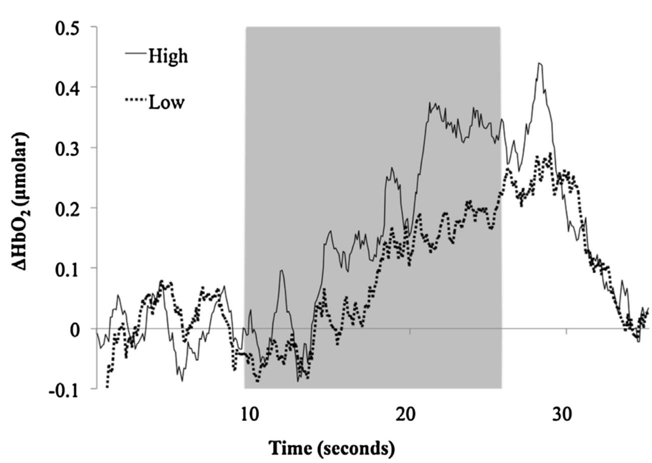

Fig. 5. Oxyhaemoglobin response to images of buildings with high and low residual scores. Eight of the 10 images with high residual scores were judged uncomfortable to view in Studies 1 and 2. Eight of the 10 images with low residual scores were judged comfortable.

Fig. 6. Examples of views used in Studies 4 and 5.

4. Study 4: ratings of real scenes and photographs

4.1. Procedure

Eleven students from the University of Essex, aged 20–24, two with corrected vision, acted as participants. The experimenter took the students on a walk around the campus and asked the participant to stand at pre-arranged locations and directed their gaze towards a particular view. The participants were required to rate the view as to how "comfortable the scene was to look at" on an 11-point Likert scale, from −5 "very uncomfortable" through 0 (neutral) to +5 "very comfortable". The participants experienced the viewpoints in different orders. Ten "natural" views comprising grass, shrubs and trees and 10 views of university buildings were presented in an order that avoided successive presentation of more than two views within the two above categories. Fig. 6 shows examples of the scenes.

At the end of the presentation the participants sat in front of the 15" screen of a laptop computer, resolution 1440 × 900 pixels. At the viewing distance of about 0.5m, the screen subtended 22° vertically. Colour photographs of the 20 scenes taken with a Canon PowerShot SX530 camera with an estimated 40° field of view (vertical) were presented for 16 s on the screen in a fixed random order using PowerPoint, and the participant was asked to rate the photographs on the same 11-point Likert scale.

4.2. Results

There were no significant differences in mean ratings for the views and for the photographs. The correlation between the ratings of a view and of its photograph was $r = 0.89$, $p < 0.001$, suggesting that photographs induced similar levels of (dis)comfort relative to the real scene. There was a good consistency between observers: the average correlation between an individual observer's ratings and the mean rating (and standard deviation) for the group was 0.79 (0.18) for views and 0.72 (0.14) for photographs. The ratings differed significantly between buildings, −0.77 (1.44) and shrubbery, 2.38 (1.25), $t(9) = 9.84$, $p < 0.001$, $d = 2.3$. Separating the images by category revealed that there was a significant correlation between a scene and its photograph for buildings, $r = 0.75$, $p < 0.05$, but not for grass shrubs and trees, $r = 0.58$, $p = 0.078$.

5. Study 5 (replication)

The procedure was the same as that for Study 4 except that 10 different students (six females and four males) of similar age (average 22 years) served as participants, and the photographs were presented on the 21.5" screen of a laptop computer with a resolution of 1920 × 1200 pixels. At the viewing distance of about 50 cm the screen subtended 23° (vertical).

5.1. Results

As before, there were no significant differences in mean ratings for the views and for the photographs, and the ratings were similarly consistent. Again, there was a strong correlation between the mean ratings of a scene and of its photograph, $r = 0.75$, $p < 0.05$. The mean ratings differed significantly between buildings −0.6 (1.50) and shrubbery, 1.27 (1.26), $t(9) = 5.95$, $p < 0.001$, $d = 1.4$. Again, separating the images by category revealed that there was a significant correlation between a scene and its photograph for buildings, $r = 0.74$, $p < 0.05$, but not for grass, shrubs and trees, $r = 0.40$, $p = 0.253$.

5.2. Discussion

We have shown that images of the modern urban environment are sometimes uncomfortable and that this discomfort can be predicted from the unnatural statistical properties of the image. We have demonstrated that images of buildings with unnatural statistical properties are associated with a relatively large haemodynamic response in the visual cortex, as is the case with other uncomfortable visual stimuli. The larger haemodynamic response is consistent with inefficient neural processing and with a greater metabolic load in consequence. We have shown that views of buildings are rated as comfortable or uncomfortable in much the same way as photographs of those views (notwithstanding the differences in viewing angle) and thereby demonstrated that our findings have implications for the design of the urban environment. In essence, the repetitive patterns in modern architecture are unnatural, and in consequence they give rise to discomfort and a higher metabolic demand on the visual cortex, consistent with neural processing that may be relatively inefficient.

It might be argued that the present findings are secondary to effects of emotional valence for example, the student attitude to the buildings in their university in Studies 4 and 5 cannot easily be separated from their more general attitude to the university as an institution. However, these effects cannot explain the results of Experiments 1–3 in which the images of buildings were likely to have been unfamiliar to all participants. In these experiments there was nothing to indicate that the uncomfortable images were attended to any differently from those that were more comfortable.

It is possible that some of the effects are attentional and arise because discomfort attracts attention to or deflects it from an image. They may also be emotional in so far as discomfort may give rise to an emotional response. This is of particular relevance in Study 3 because attention and emotion are known to affect the haemodynamic response, e.g. Henson and Mouchlianitis (2007). We measured the response from posterior head regions and therefore from superficial layers of the visual cortex. fMRI studies have shown strong attentional effects on the haemodynamic responses of human primary visual cortex (e.g. Ghandi et al., 1999). Although attention and emotion may have mediated the effects of image structure on the amplitude of the haemodynamic responses observed in Study 3, it is likely to be because of the discomfort, given the findings of our other studies, and the convergence in the literature reviewed in the introduction.

Studies of aesthetics in urban design (Nasar, 1994), have already appreciated the role of natural features (Sullivan & Lovell, 2006) and tools have been developed for improving the aesthetics of urban streetscapes (Gjerde, 2011). Visual discomfort has been discussed from the point of view of lighting design (Steemers, 1994) but until recently is has not been possible to find a numerical expression for discomfort from visual aspects of building structure. Discomfort can be predicted from simple mathematical properties of the visual image (Penacchio & Wilkins, 2015), and here we show that these properties are of importance for brain metabolism.

Some of the beneficial effects of green exercise (Pretty, Griffin, & Sellens, 2004; Pretty, Peacock, Sellens, & Griffin, 2005) may arise because natural scenery avoids the repetitive patterns common in the urban environment.

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