Visual discomfort and blur

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Certain visual stimuli, such as striped patterns and filtered noise, have been reported to be uncomfortable. Some filtered noise patterns judged as uncomfortable are those with a relative decrease in contrast amplitude at high spatial frequencies, compared with the statistics typical of natural images. Decreased amplitude at high spatial frequencies is a characteristic often associated with perceived blur. Additionally, the distribution of contrast across spatial frequencies also provides a cue for the accommodation (focusing) response. The purpose of this study was to investigate the relationship between excess low spatial frequency information, discomfort judgments and perceived blur. Results of these experiments show that a relative reduction in high spatial frequency contrast results in both increased discomfort and perceived blur. This is both in artificial and natural stimuli. A possible explanation for this relationship based on accommodation responses is proposed.

Introduction

Visual discomfort

The aim of this study is to investigate the relationship between visual discomfort judgments and image manipulations that could cause an image to be perceived as blurred. Visual discomfort is the subjective adverse effects encountered on viewing certain stimuli. Effects have been reported to include headaches, eyestrain, and blurred vision (Sheedy, Hayes, & Engle, 2003). Stimuli eliciting these effects include striped patterns (e.g., Wilkins et al., 1984), certain text stimuli (e.g., Nahar, Sheedy, Hayes, & Tai, 2007) and filtered noise patterns (Fernandez & Wilkins, 2008; Juricevic, Land, Wilkins, & Webster, 2010; O'Hare & Hibbard, 2011). Manipulations of spatial frequency content affect discomfort judgments, and it has been suggested

that deviations from the statistics of natural images causes the discomfort (Juricevic et al., 2010).

Natural images

The statistics of natural images are important as a basis for comparison of uncomfortable images. Natural images have reliable statistical properties. In particular, Fourier analysis of natural images reveals that luminance amplitude falls with increasing spatial frequency, resulting in a $1/f^{\beta}$ Fourier amplitude spectrum, where β is approximately 1 (e.g., Redies, Hasenstein, & Denzler, 2007; Tolhurst, Tadmour, & Chao, 1992). This means that there is typically more contrast energy at the lower spatial frequencies than at the higher ones. This can be seen in Figure 1A; luminance amplitude is plotted against log spatial frequency in an image of some vegetables. It is thought that the visual system is optimized to encode stimuli with the luminance statistics of typical natural images (e.g., Field, 1987). It has been suggested that visual discomfort could arise from stimuli that do not have these natural statistics, and therefore are not processed optimally (Juricevic et al., 2010).

Uncomfortable images

Research using filtered noise patterns has shown that deviations from natural image statistics affect discomfort judgments. For example, Fernandez and Wilkins (2008) showed that filtered noise patterns with luminance amplitude falling with spatial frequency as $1/f^{1}$ are judged as more comfortable than filtered noise patterns with a peak in the amplitude spectrum, i.e., images with an excess of spatial frequency information around 3 c/°. O'Hare and Hibbard (2011) asked observers to compare filtered noise patterns with peaks at a range of different spatial frequencies in the
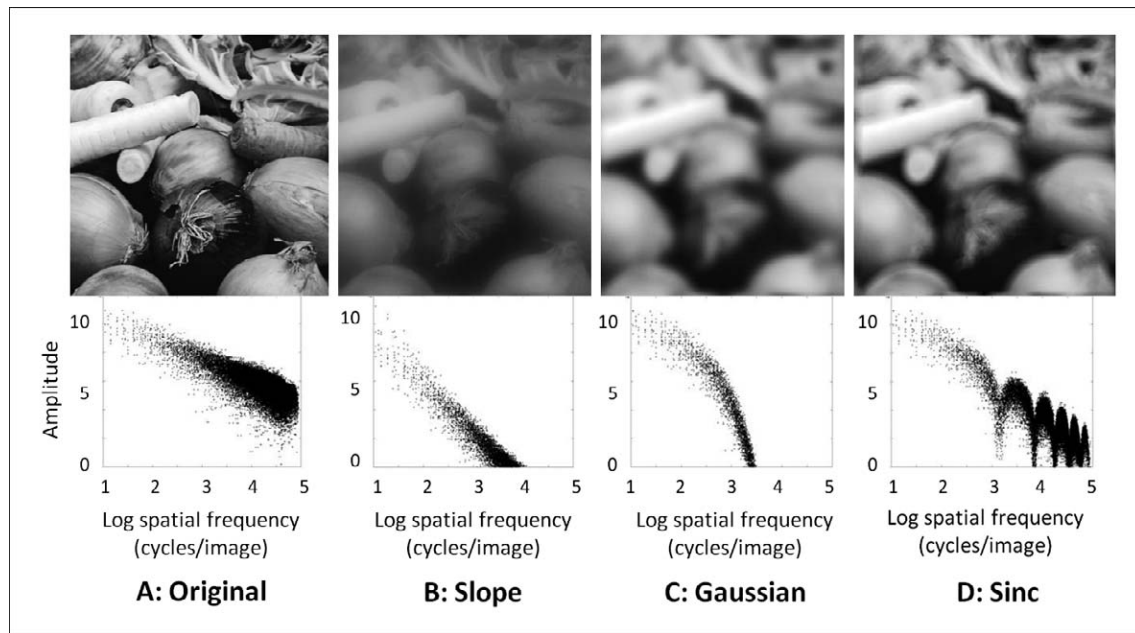
Figure 1. Natural images and their corresponding luminance amplitude spectra. (A) original natural image; (B) the slope exponent (β) of the original image (1.45) has now been increased to 2; (C) a Gaussian blurred version of the original image; (D) a sinc-filtered version of the original image.

amplitude spectrum (centered on 0.19 to 12 c/°). It was shown that spatial frequencies around 0.75 to 1.5 c/° were judged more uncomfortable than the higher ones in the range tested. Simply adding excess contrast energy is not the only manipulation of the amplitude spectrum that causes discomfort judgments to vary; Juricevic et al. (2010) showed that increased β (a steeper amplitude spectrum with relatively more low spatial frequency information) increased discomfort judgments of both filtered noise patterns and Mondrians (patterns of randomly positioned rectangles). Figure 1B shows a version of the original image with an increased amplitude spectrum exponent.

Blur

A relative decrease in high spatial frequency information could potentially be interpreted as blur (Campbell, Howell, & Johnstone, 1978). However there are many different ways of quantifying blur. Global luminance statistics are one measurement of blur; others include the steepness of the local luminance gradients in the image. This can be illustrated by considering a square wave (step edge) compared to a sine wave luminance gradient. One way to characterize the image is the amplitude spectrum, which relates to the relative amplitude of information present in the whole image at different spatial scales. In a step edge, the amplitude of the harmonics falls with a $1/f$ pattern: Higher harmonics have smaller amplitudes. Removing

harmonics from this waveform has the effect of decreasing the high spatial frequency content, decreasing the local luminance gradients and making the image more like a sine wave.

The $1/f$ relationship is not the only manipulation that affects the local luminance gradients and perceived blur of images. Phase manipulations affect the luminance gradients of waveforms (e.g., Badcock, 1984) and so might be expected to affect blur. As an example, consider the difference between a sharp, step edge (all scales of information in-phase) compared to a smooth decline of contrast (that can result when components are out-of-phase). Thus images can have the same amplitude spectrum, but a shallower luminance gradient, if the component spatial frequencies are out-of-phase compared to in-phase.

The steepness of the luminance gradients can be manipulated by either reducing the amplitude at high spatial frequencies, thus increasing the slope of the amplitude spectrum, or by changing the phase relationships of the information in the image (e.g., Badcock, 1984). Either a loss of high spatial frequency information overall, or phase shifts in local luminance gradients may contribute to blur perception. If the steepness of local luminance gradients is the cause of discomfort, it might be expected that blur induced by phase as well as amplitude manipulations also affect discomfort judgments. While the distinction is straightforward in artificial stimuli, this becomes more complex when considering blur in natural images.

There are different techniques for introducing blur to natural images, but a common method involves filtering techniques such as Gaussian or sinc filtering. Figure 1C shows a Gaussian blurred image, and the corresponding amplitude spectrum. Gaussian filtering has been used in the past as a model of optical blur (e.g., Bocheva & Mitriani, 1993). However, this is limited as a model of optical blur, as it does not contain the correct phase relationships that result from optical phenomena such as aperture effects. As light passes through the pupil it is subjected to diffraction. This creates characteristic phase reversals in the resulting retinal image. These phase reversals appear as banding around the edges in the image. Sinc filtering, which also introduces these phase reversals, has been suggested to be a potentially more realistic model of optical blur than Gaussian blur (Murray & Bex, 2010). The difference between Gaussian and sinc filtering can be seen in Figure 1; the different filters affect the shape of the amplitude spectrum and the local luminance gradients. Whether this distinction is important is unclear as yet; therefore, both models of optical blurring were used in the study.

Accommodation responses

Accommodation responses provide one possible reason why blur might be uncomfortable. Defocus blur is characterized by a loss of high spatial frequency information in the image of the fixated object. This is a possible cue to drive the accommodation (focusing) responses—this blur can be reduced by refocusing to the appropriate distance. It is thought that the goal of the accommodation response is to maximize retinal image contrast, but unfortunately, there is, as yet, a limited understanding of exactly what spatial frequency information the accommodative system uses (MacKenzie, Hoffman, & Watt, 2010). There is also uncertainty about whether the system uses local or global image statistics to achieve this end. MacKenzie et al. (2010) have argued that the global amplitude of spatial frequency information is critical for driving accommodation responses: they consider only the Fourier amplitude spectrum in their model of how stimulus spatial frequency content affects accommodation responses. By contrast, Day, Gray, Seidel, and Strang (2009) make the case that the critical information for accommodation responses is contained in the steepness of the luminance gradients. It has been suggested that coarse accommodation responses might be driven by the low spatial frequencies, which are then refined by using the higher ones (Charman, 1979). This is important as the insufficient high spatial frequency information in some stimuli might provide inadequate information to drive accommodation. Inadequate

information for the accommodative system could potentially leading to uncertainty in the response, which could manifest itself as increased microfluctuations (Day et al., 2009), for example. Increased microfluctuations could potentially cause discomfort directly from muscle fatigue. Alternatively it is possible that sensory discrepancies resulting in the increased uncertainty are simply uncomfortable due to the increased computational demands.

Simmers, Gray, and Wilkins (2001) showed that, for some individuals who experience visual stress, microfluctuations in accommodation are related to visual discomfort. Individuals for whom visual stress was alleviated by the use of tinted lenses had a greater power in low frequency accommodation fluctuations than a control group, and this reduced when wearing a tinted or neutral-density lens. Individuals who experience relatively large fluctuations in accommodation experience visual stress; the same underlying mechanism might be expected to cause discomfort in the general population when viewing stimuli that increase variability in accommodation.

Informative stimuli for the accommodation response

An informative stimulus to drive accommodation responses would provide sufficient amounts of the relevant (higher) spatial frequency information. Natural images have a $1/f^1$ amplitude spectrum, meaning they contain a range of spatial frequencies.

Conversely, if an image has little spectral power at high spatial frequencies, then luminance gradients might not change much with defocus blur. This will render the defocus cue to accommodation uninformative, which might increase uncertainty in the accommodative response. This uncertainty might then lead to inefficient, inaccurate accommodation responses.

Current experiment

The aim of this study is to assess the relationship between the relative spatial frequency content of images, visual discomfort, and perceived blur. This was investigated first using readily controllable, artificial stimuli to show the effects of luminance profile manipulations on discomfort judgments, to determine whether loss of spatial frequency information, or change in luminance profile, was the deciding factor for any possible discomfort judgments.

The experiment was then extended to more complicated natural images, using two different models of optical blur to assess the effect of phase reversals. Also, images were chosen with a range of initial amplitude

spectra, to see if deviation from the original, or an ideal $1/f^1$ statistic, is critical.

General methods

Methods used were similar for all experiments. Therefore general methods will first be described.

Apparatus

Stimuli were presented at a distance of 1 m, on a 21-inch Sony Trinitron monitor with screen resolution of 1680×1050 and a vertical refresh rate of 60 Hz. Images were created and displayed using MATLAB 7.1 (The Mathworks Inc., 2005, Natick, MA) and the Psychophysics Toolbox (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997). The luminance response of the monitor was measured and calibrated using a Minolta Luminance Meter, LS-110 photometer. The luminance of the mid-gray background was 38.5 cd/m^2, the luminance range was from 3 to 71 cd/m^2. Head movements were stabilized by use of a chin rest.

Stimuli

All stimuli were 840×840 pixel images. These were spatially vignetted with a circular window of radius of $5.71°$. Outside of this radius the luminance profile at the edge of the window fell with a Gaussian profile of $\sigma = 0.93°$. The size of the visible pattern subtended approximately $8.53°$. The background was held at a constant mid-gray luminance level.

Observers

All participants in all experiments in this study were reimbursed 5 pounds per hour for their time. The entire study was approved by the University of St Andrews Teaching and Research Ethics committee, in accordance with the Declaration of Helsinki.

Procedure

A two-interval-forced-choice (2IFC) task was used. Stimuli appeared on the screen for 0.6 s each, with a delay of 0.1 s between them, during which a mid-gray screen was presented. Stimuli were replaced with a mid-gray background during which the observer responded. Observers indicated which of the two stimuli appeared more uncomfortable by pressing the corresponding left (first interval) or right (second interval) arrow key.

Analysis

Raw scores were relative discomfort judgments: the frequency a particular image or image category was chosen as more uncomfortable out of the paired comparisons. These raw scores were then converted into scores on a Thurstone scale (Thurstone, 1927; Tsukida & Gupta, 2011). Each stimulus was compared with each other stimulus N times. The first step was to calculate, for all comparisons between two stimuli A and B, the number of times that stimulus A was judged to be the more uncomfortable. These counts were then converted to probabilities by dividing by the number of comparisons between A and B. The difference between A and B on the discomfort scale was then calculated as the inverse of the standard normal cumulative distribution function. For example, if stimulus A was chosen as the more uncomfortable on half the trials, the calculated difference value is 0. The final discomfort for each stimulus is then given by the mean of the calculated difference in discomfort in comparisons between A and all other stimuli. A problem for this method arises when one stimulus is always (or never) chosen as the more uncomfortable, given a probability of 0 or 1; this creates a scale difference of $\pm\infty$. To avoid this, counts of $1/N$ and N/N were replaced with values of $(1/2)/N$ and $[N - (1/2)]/N$ before the calculation of probabilities, where N is the number of appearances of each particular stimulus. This is a conservative strategy, since it effectively reduces the confidence in the comparison between the two stimuli (Tsukida & Gupta, 2011). This process was repeated for each observer to create individual scales of discomfort. These individual scales of discomfort were then averaged to obtain the mean discomfort scale across observers.

Results were analyzed using repeated-measures ANOVA. Relevant Greenhouse-Geisser corrections were used to correct for violations of assumptions of the ANOVA where necessary.

Experiment 1: Discomfort judgments of simple stimuli

Method

Stimuli

Stimuli were circular gratings, consisting of a fundamental frequency of 0.375, 0.75, or 1.5 c/°, plus up to four harmonics. There were two experimental sessions, in which either the number of harmonics or
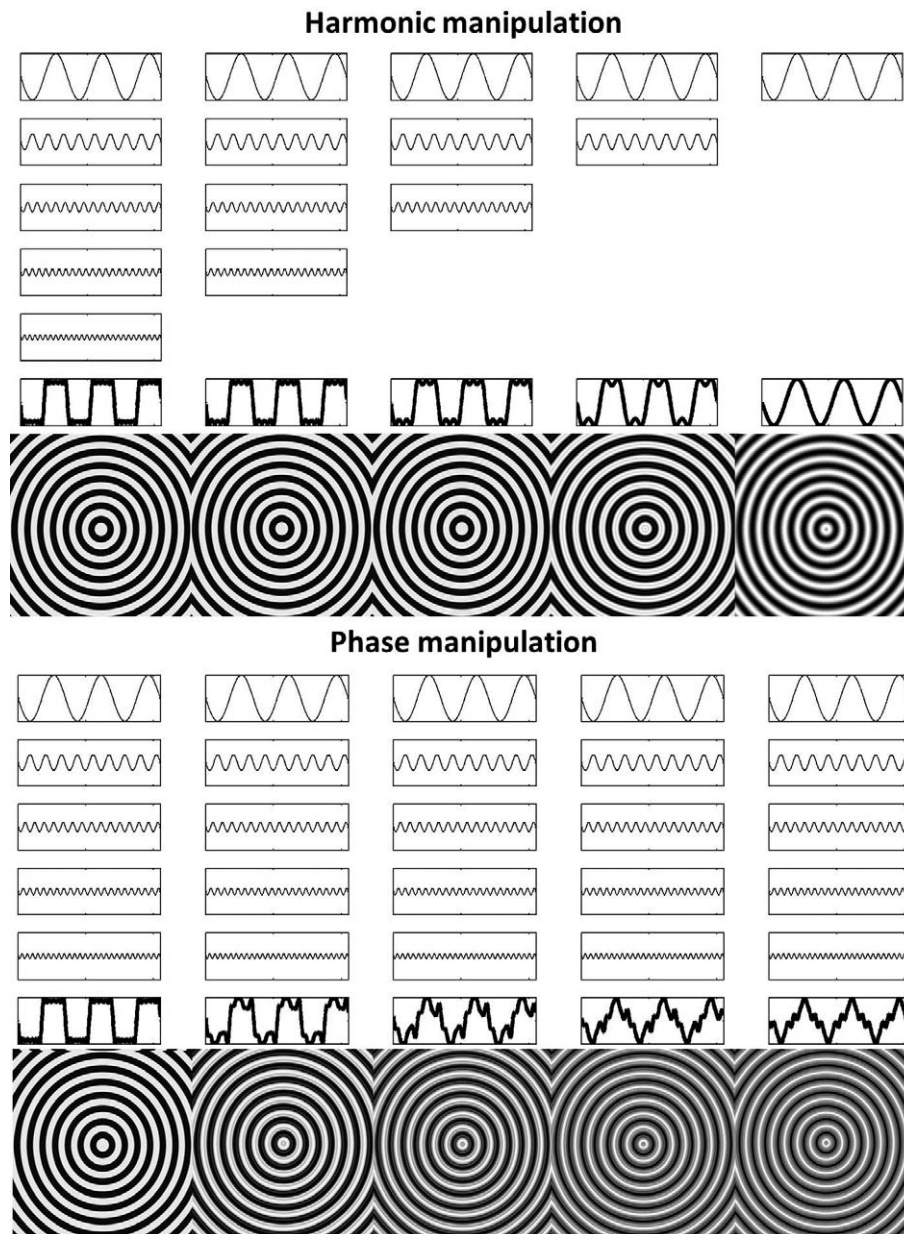
Figure 2. Stimulus luminance profiles. Top: example stimuli for the harmonic manipulated stimuli. Constituent harmonics are added together to create the total waveform. Total waveform is shown in bold. Resulting image is shown below.

the relative phases of the harmonics were varied. Figure 2 shows examples of the stimuli and how they were created in terms of their luminance profile. In the first, harmonic manipulation session, the number of harmonics was varied. In all cases, the fundamental frequency component was present. This was either presented alone, or accompanied by the first harmonic, the first two harmonics, the first three harmonics, or the first four harmonics (see Figure 2). In all cases, the fundamental and all of the harmonics were in square-wave phase. In the second, phase manipulation session, all the stimuli consisted of the fundamental frequency plus all four of the first harmonics. The phase of the first harmonic was shifted relative to that of the fundamental by 0°, 45°, 90°, 135°, or 180° to create five different stimuli for each spatial frequency. The first harmonic was shifted relative to the fundamental and other harmonics as this resulted in the greatest difference in the luminance gradient.

Observers

Fourteen naïve student observers took part in the experiment, all with normal or corrected-to-normal vision. Efforts were made to ensure that the same observers participated in both phase and harmonic sessions; however, this was not always possible. Three
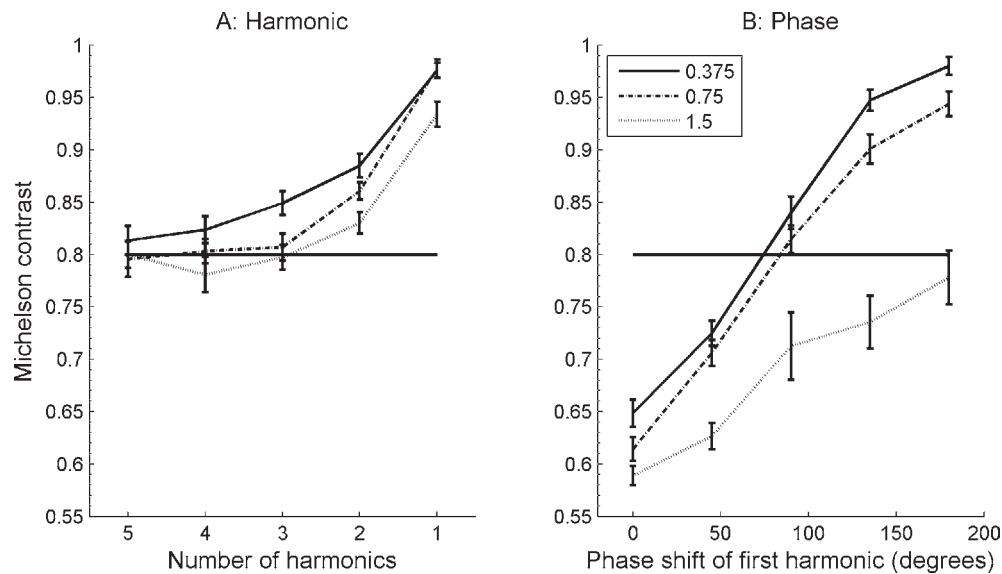
Figure 3. Contrast matching results for Experiment 1. (A) Average physical (Michelson) contrast needed for harmonic manipulated stimuli to be perceived as matched. (B) Average physical (Michelson) contrast needed for phase manipulated images to be perceived as equal contrast. The solid black line indicates the contrast of the standard. Error bars show ±1 standard error.

out of the 14 observers participated in the harmonic session only, and three out of the 14 participated in the phase session only. The participants ranged in age from 18 to 29 years; mean age was 21.6 years. The sessions had no particular order—some individuals performed the harmonic session first, others the phase session.

Procedure

Observers were asked initially to match stimuli for perceived contrast using a self-adjustment technique. Stimuli were presented three times each in random order, and observers adjusted the contrast of the test stimulus to match the perceived contrast of the standard stimulus. The standards were the 0.375 c/° sinusoidal stimulus (in the harmonic session) and the 0.375 c/° 180° phase-shifted stimulus (in the phase session). The Michelson contrast of these standards was set at 0.80; observers adjusted the contrast of all other stimuli to match the perceived contrast of this standard. Each observer made three settings for each image to equalize the test and the standard images for contrast using the keys. Average Michelson contrast settings across observers for each image are shown in Figure 3.

Observers then took part in a two-interval-forced-choice (2IFC) discomfort rating experiment. The contrasts of the stimuli were set to be perceptually equal, based on the responses of each observer in the previous part of the experiment. It should be noted that although average results are plotted in Figure 3, each individual was presented stimuli according to their own unique results from the contrast matching experiment.

There were 20 repetitions of each comparison; each of the 15 stimuli was compared to all of the others.

Results

Figure 3 shows the variation in the contrast needed for each of the stimuli to be perceived as having equal contrast. In the harmonic manipulated session more contrast was needed for stimuli with fewer harmonics. In the phase manipulated session, the more in-phase a stimulus was, the less contrast was needed to make this match the 180° phase-shifted standard. Similar trends (not shown) were evident when the data were plotted in terms of their RMS contrast, rather than Michelson contrast.

Figure 4A plots stimulus discomfort scores against increasing number of harmonics for each of the three fundamental frequencies. The results of a 3 (fundamental frequency) × 5 (number of harmonics) repeated-measures ANOVA showed a main effect of the number of harmonics, $F(1.2, 16.4) = 6.05$, $p < 0.05$. There was no significant effect of spatial frequency, $F(1.3, 16.7) = 0.11$, $p = 0.80$. There was no significant interaction, $F(2.1, 27.7) = 1.63$, $p = 0.21$.

Figure 4B plots discomfort scores against increasing phase displacement of the first harmonic for three fundamental frequencies. The results of a 3 (fundamental frequency) × 5 (magnitude of phase shift) repeated-measures ANOVA showed there to be no significant effects of phase, $F(1.9, 20.6) = 1.21$, $p = 0.30$, fundamental frequency, $F(1.1, 14.9) = 1.17$, $p = 0.32$, or
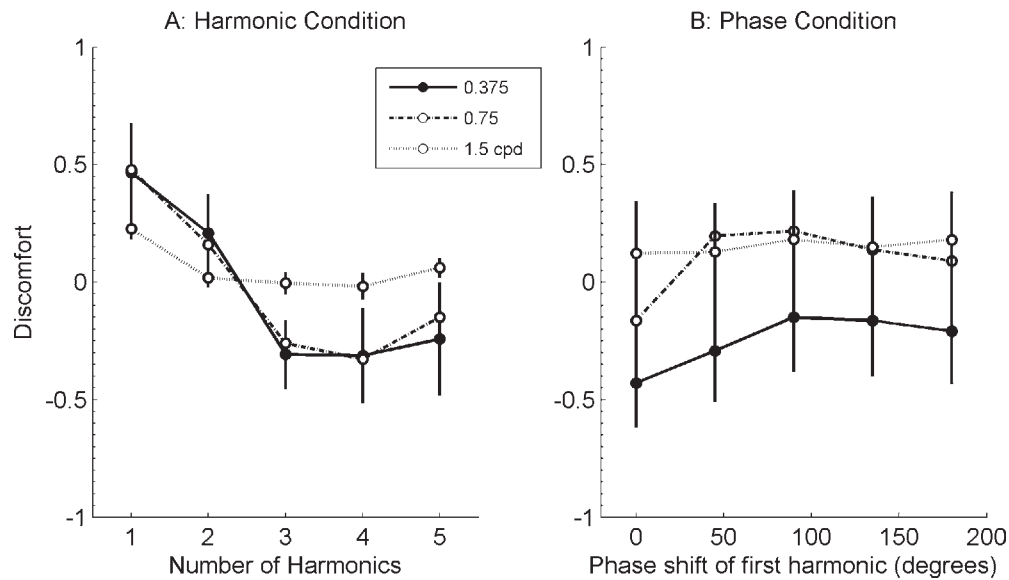
Figure 4. Discomfort scores for Experiment 1. (A) Thurstone scaled discomfort scores against increasing number of harmonics for three fundamental frequencies. (B) Thurstone scaled discomfort scores against increasing phase difference of the first harmonic for three fundamental frequencies.

any interaction of fundamental frequency and phase, $F(3.0, 38.9) = 0.81$, $p = 0.50$.

Discussion

The results showed an effect of the presence of high spatial frequency information on subjective discomfort judgments for simple stimuli. Removing high spatial frequency components increased discomfort. A concentration of visual information at low spatial frequencies has been associated with perceived blur in simple stimuli (Campbell et al., 1978). This suggests that perceived blur and visual discomfort are related, either directly, in a causal relationship, or possibly that both are influenced by a common mechanism for both subjective attributes that depends on relative high spatial frequency information.

There was no significant effect of manipulations of the luminance gradient induced by increasing the phase difference of the first harmonic on perceived discomfort. This suggests that steepness of the luminance gradient itself cannot account for the differences in discomfort judgments seen in the harmonic manipulated stimuli.

The actual luminance gradients presented to each participant varied, depending on the contrast settings that were made. Figure 5 shows the average maximum luminance gradients of each of the stimuli presented. From Figure 5 it can be seen that there is a reduction in maximum luminance gradient with decreasing number of harmonics and increasing phase shift, and there are
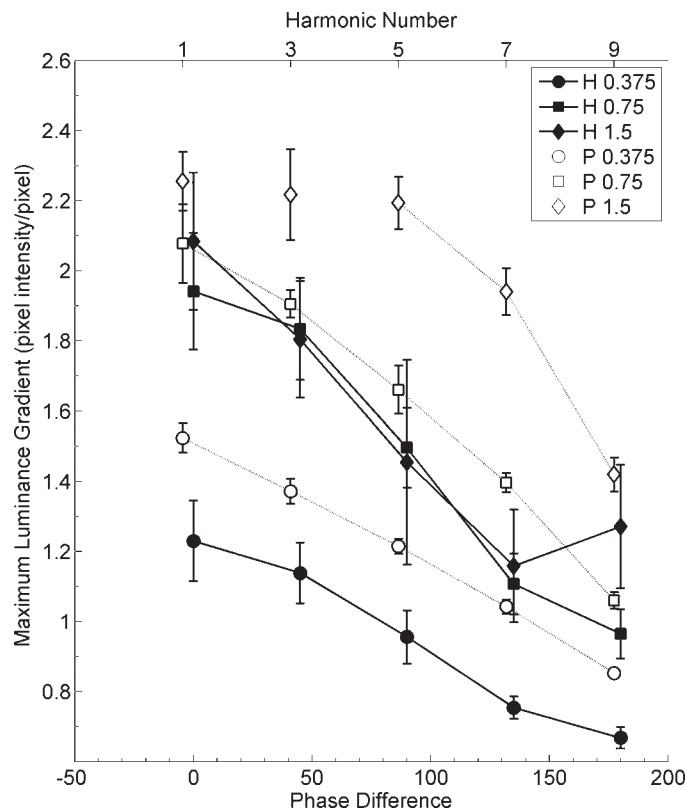

Figure 5. Average maximum luminance gradients of the presented stimuli. Stimulus luminance gradients varied over individuals: Each was presented their own unique set of stimuli, matched for perceived contrast.
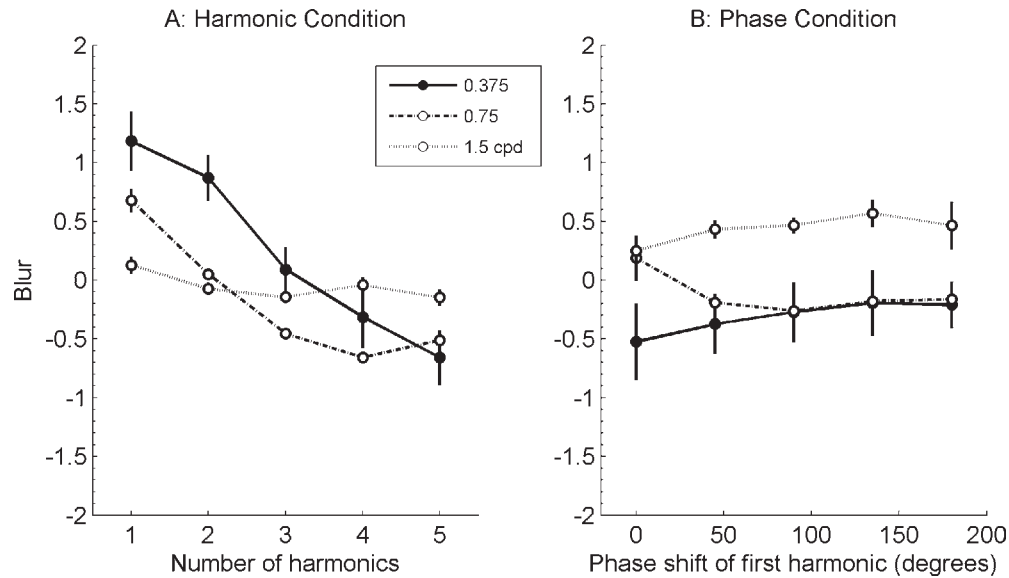
Figure 6. Blur judgments for Experiment 2. A: Thurstone-scaled blur judgments against number of harmonics for three fundamental frequencies. (B) Thurstone-scaled blur judgments against phase difference of the first harmonic for three fundamental frequencies.

differences between the fundamental frequencies, but overall there is no large difference between the two sessions. The phase-manipulated stimuli tend to be higher contrast than the harmonic-manipulated stimuli. It could be argued that physical contrast could account for the increased discomfort judgments for the harmonic-manipulated stimuli. However, as the phase-manipulated stimuli also showed similar contrast increases, but no evidence of increased discomfort judgments, physical contrast alone is insufficient to account for the data.

The harmonic manipulations of this experiment affected discomfort judgments, and the phase manipulations did not. As both manipulations affected the luminance gradients, it was expected that they may also affect perceived blur. To establish whether this was indeed the case, in the second experiment observers were asked to judge the apparent blur of stimuli, using the same setup as before.

Experiment 2: Blur judgments of simple stimuli

The aim of Experiment 2 was to ascertain whether the stimuli identified as uncomfortable from Experiment 1 are actually perceived as blurred.

Method

Six undergraduate observers took part in the study. Two had taken part in Experiment 1; the other four were completely naïve to the purposes of the experiment. The contrast matching task was exactly the same as in Experiment 1. This time, participants were asked to choose the more blurred stimulus (not the more uncomfortable) of each pair, and indicate their response using the left and right arrow keys. They were asked to guess if they felt that neither stimulus was blurred.

Results

Figure 6A plots Thurstone-scaled blur judgments against increasing number of harmonics. This shows there was an effect of the number of harmonics on perceived blur; the fewer harmonics present, the more blur was perceived. The results of a 3 (fundamental frequency) × 5 (number of harmonics) repeated-measures ANOVA showed there to be a significant effect of number of harmonics, $F(1.63, 8.17) = 8.57, p < 0.01$. Stimuli with more harmonics were perceived as less blurred than stimuli with fewer harmonics. There was no significant effect of fundamental frequency, $F(2, 10) = 1.68, p = 0.24$. There was a significant interaction between number of harmonics and fundamental frequency on blur judgments, $F(2.5, 12.6) = 5.86, p < 0.05$. Posthoc one-way repeated-measures ANOVA showed there to be an effect of the number of harmonics for the lowest two fundamental frequencies, $F(1.4, 7.0) = 13.91, p < 0.01$; and $F(4, 20) = 7.08, p < 0.01$, for 0.375 and 0.75, respectively). However, there was no significant effect of number of harmonics for the highest fundamental frequency, $F(1.4, 7.1) = 0.34, p = 0.65$.

Figure 6B plots the perceived blur against phase manipulation. The results of a 3 (fundamental frequency) × 5 (phase shift) repeated-measures ANOVA showed there to be no significant effects of fundamental frequency, $F(2, 10) = 1.51$, $p = 0.27$, phase shift, $F(1.8, 8.9) = 1.17$, $p = 0.35$, or interaction between phase shift and fundamental frequency on blur judgments, $F(2.5, 12.7) = 1.34$, $p = 0.30$.

Discussion

There was a significant effect of the number of harmonics on perceived blur. As this is the same pattern of results as Experiment 1, this suggests that there might be a relationship between perceived blur and discomfort judgments. There was also an interaction between the number of harmonics and the fundamental frequency on perceived blur judgments: the effect of harmonic removal was more evident for the lower fundamental frequencies compared to the highest fundamental frequency. This could be because the luminance gradient of the highest spatial frequency fundamental is too steep by itself for the loss of higher spatial frequency information to have much effect.

The phase shift manipulation showed no effects on either discomfort judgments or blur judgments. This could well indicate that it was the loss of high spatial frequency information that was responsible for the increased judgments of discomfort and blur. This is indicative that there might be a common mechanism underlying both these processes.

Experiment 3: Blurring natural images

The first two experiments showed that, for simple circular approximations to square-wave stimuli, removing high frequency components increased both visual discomfort and perceived blur. Since the removal of high spatial frequency information also increases apparent blur in more complicated images (Murray & Bex, 2010; Webster, Georgeson, & Webster, 2002), we next investigated whether this also leads to increased visual discomfort for complex natural images. Experiment 3 has three aims. The first was to investigate the effects of increasing blur on visual discomfort judgments using natural stimuli. The second was to investigate if there is a difference between sinc-filtered images (which contain phase reversals) and Gaussian filtered images (which do not). The third was to see if visual discomfort judgments depend on deviation from the original statistics of the image, or deviation from a possibly 'ideal' $1/f^1$ statistic.

Method

Sixty grayscale natural images were taken from the Hibbard (2008) database. Images were 1201 × 1201 pixels in size, taken using a calibrated Nikon Coolpix 4500 digital camera. Images were calibrated to correct for luminance. The spatial resolution was 1 pixel/arcmin. These were from two general categories: distant scenes (e.g., woodland scenes, beach scenes), or close-ups of vegetables, rocks, and seaweed. Thirty outdoor scene images were used; these had a mean slope exponent (β value, where $1/f^\beta$) of -1.19 ($SD = 0.29$). Thirty close-up images were also used; these had a mean slope exponent (β value) of -1.10 ($SD = 0.20$). The 10 most extreme examples from each category were chosen for the test stimuli; the 10 steepest slopes in the close-up category (mean β value $= -1.39$, $SD = 0.06$), the ten shallowest slopes in the outdoor scene category (mean β value $= -0.95$, $SD = 0.06$). The mean β values of the two categories (steep and shallow) were significantly different according to an independent pairs t-test, $t(18) = -28.39$, $p < 0.001$.

Images were filtered in the Fourier domain with either a Gaussian or sinc filter. The Gaussian filter is defined in the frequency domain as:

$$A = k_g e^{\left(-\frac{f^2}{2\sigma^2}\right)} \tag{1}$$

Here, A is the amplitude of the filter, corresponding to the amount of the signal transmitted, f is the frequency, σ is the standard deviation in pixels, and k_g is the normalization constant. Gaussian filters were of varying sizes: $\sigma = 8$, 16, or 32 pixels in the frequency domain (Fourier transform, see Equation 1). This gave Gaussian filters of width at half height 20 pixels, 38 pixels, and 76 pixels, respectively.

Sinc-filtered images were created by multiplying the Fourier-transform of the image with a sinc filter, which was defined in the frequency domain as:

$$A = k_s \frac{sin\left(\frac{\pi f}{\lambda}\right)}{\frac{\pi f}{\lambda}} \tag{2}$$

Here λ is comparable to the σ values of the Gaussian filter (see Murray & Bex, 2010). k_s is the normalization constant. λ was chosen to be 2.9 times σ values (23, 46, 93), to result in three levels of blur. These levels of λ were chosen as the perceived blur from these filters is comparable to the level of perceived blur from the Gaussian filters used (Murray & Bex, 2010).

The two types of blurring (sinc and Gaussian) at three levels created six versions of each image. All images were matched for RMS contrast. The RMS contrast was set at 0.3 for all images in the current experiment. Thirteen naïve undergraduate students with normal or corrected-to-normal vision participated
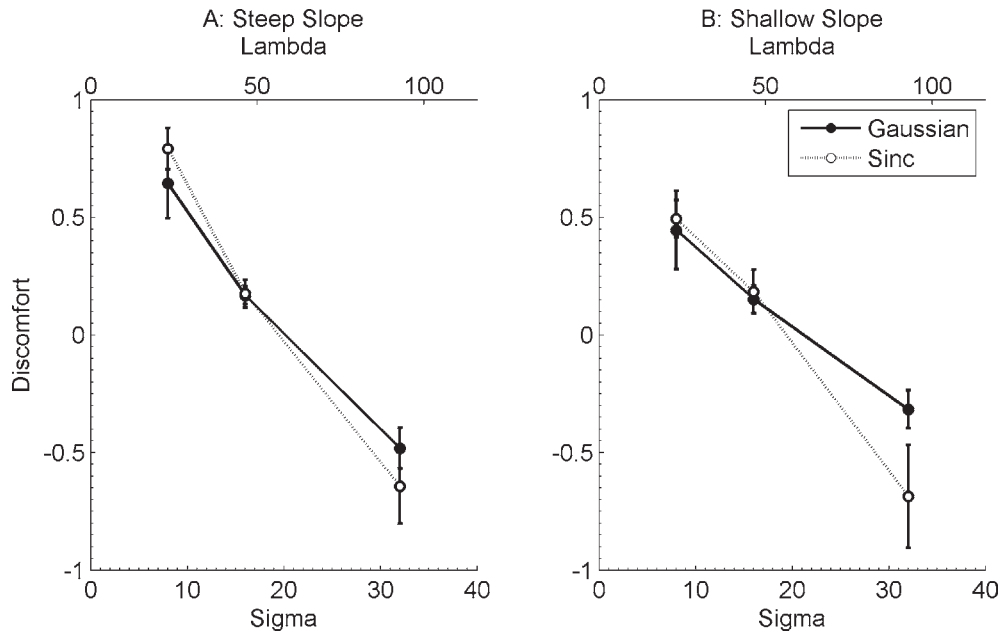
Figure 7. Discomfort judgments for Experiment 3. (A) Thurstone-scaled discomfort judgments against decreasing blur for natural images for the steep initial slope stimuli. Blur is comparable amounts of Gaussian or sinc blur. σ and λ values are defined in frequency space; therefore, small values indicate large amounts of blur. (B) Thurstone-scaled discomfort judgments against decreasing blur for natural images for the shallow initial slope stimuli.

in the study. There were two sessions, one consisting of steep slope images, the other of shallow slope images. Ten participants completed the steep slope session first; three completed the shallow slope session first. Each of the six categories of blurring was compared to each of the other categories, resulting in 15 comparisons. Ten images in one category were compared with 10 from the other category, so that there were 10 images (from the first category) $\times$ 10 images (from the second category) $\times$ 15 category comparisons = a total of 1500 trials. The number of times a stimulus category was chosen as more uncomfortable was recorded. This was repeated for each of the two sessions (steep, shallow initial slope).

Results

Figure 7A plots discomfort judgments against σ (for the Gaussian filter; lower axis) or λ (for the sinc filter; upper axis) values for the steep slope stimuli. There was a significant main effect of increasing blur, $F(1.3, 15.2) = 31.11$, $p < 0.01$; increasing blur resulted in increased discomfort judgments. There was no significant effect of type of blur (Gaussian or sinc), $F(1, 12) = 1.47$, $p = 0.25$. There was no significant interaction between the type of blur and the amount of blur, $F(1.4, 16.4) = 0.61$, $p = 0.50$.

Figure 7B plots discomfort judgments against σ (lower axis) and λ (upper axis) for the shallow slope images. There was a significant main effect of

increasing blur only, $F(1.1, 12.9) = 13.75$, $p < 0.01$; there were no effects of type of blur, $F(1, 12) = 3.27$, $p = 0.10$, and no interaction, $F(2, 24) = 1.71$, $p = 0.20$.

Discussion

There was a strong effect of blur on discomfort judgments in natural images—the more blur, the more often the stimulus was judged the more uncomfortable of the pair of images presented. The results of this experiment are consistent with Experiment 1: Blur was associated with discomfort judgments, this time for natural as well as simple stimuli. There was no difference between the steep and shallow initial slope of the stimuli, therefore initial slope is not important to discomfort judgments.

General discussion

The aim of this study was to investigate the relationship between low spatial frequency information, visual discomfort, and perceived blur. Initial experiments investigated this relationship using simple stimuli and showed that a loss of high spatial frequency information, but not the shifting of the relative phase of the first harmonic, resulted in increased discomfort. A subsequent experiment showed that the same stimuli judged as more uncomfortable were also judged as

more blurred, suggesting that there was an association between the loss of high spatial frequency information, discomfort and image blur. This was further investigated using natural images. Increasing blur led to increased discomfort judgments, for both sinc and Gaussian blurred natural images. This supported the finding of the initial experiments using artificial stimuli.

One potential reason for discomfort from blurred images could be that blurring the image impoverishes the feedback for the accommodation response. The accommodation system needs a certain amount of higher spatial frequency content to inform the response. The stimuli judged as uncomfortable lack these higher spatial frequencies as they are blurred. Therefore they might not provide the necessary signal for the accommodative response to focus. This could be tested directly by measuring accommodative responses using an autorefractor. Stimuli that are less informative for the accommodative system might lead to greater uncertainty in the accommodative response; it would be predicted that this would lead to increased microfluctuations (Day et al., 2009). If an impoverished signal for accommodation is responsible for discomfort, this could be for at least two reasons. An increase in microfluctuations might be the direct source of discomfort. Alternatively, discomfort could arise from the fact that these microfluctuations do not reduce the apparent blur, as they would be expected to in the case of an image that was optically defocussed. In future research, it would be valuable to repeat the experiments with presbyopes to determine the effect of aging on this potential source of discomfort.

However, there is another possible account. Juricevic et al. (2010) suggested that deviations from the statistics of natural images are uncomfortable due to inefficient neural coding in the brain, instead of oculomotor responses. One way in which efficiency could be achieved is to try to ensure a sparse response to typical natural stimuli. A sparse encoding of images is one that produces a strong response in only a relatively small proportion of neurons, and has been shown to be a useful characterization of the coding of natural images in the primary visual cortex (e.g., Field, 1994; Field, 1999; Olshausen & Field, 2004; van der Schaaf & van Hateren, 1996). Stimuli resulting in inefficient (non-sparse) neural coding might be uncomfortable as they are again costly in terms of metabolic resources.

This is not to suggest that the accommodation and neural accounts are competing. There are many different aspects of visual discomfort, and these may well account for two separate aspects. For example, the blurred vision and eyestrain reported under some circumstances, such as prolonged reading (Sheedy et al., 2003), might be indicative of poor accommodative responses. By contrast, cortical explanations can better account for why other stimuli, such as sharp, high contrast square-wave patterns are uncomfortable to non-clinical populations (Wilkins et al., 1984), and can additionally elicit neural activity typical of seizures in epilepsy sufferers (Wilkins, Darby, & Binnie, 1979). Future study would be directed towards discriminating between these two possibilities, potentially assessing the separable effects on clinical populations, and optics in non-clinical populations.

Acknowledgments

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