



Visual discomfort and flicker



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ABSTRACT

Flickering lights can be uncomfortable to look at and can induce seizures in observers with photosensitive epilepsy. However, the temporal characteristics contributing to these effects are not fully known. In the spatial domain, one identified source of visual discomfort is when images have Fourier amplitude spectra that deviate from the natural ($\sim 1/\text{frequency}$, $1/f$) statistical characteristics of natural scenes, especially if they contain excess energy at the medium frequencies at which the visual system is most sensitive. We tested for analogous effects in the temporal domain, manipulating both the amplitude and phase spectra of the flicker. Participants judged the relative discomfort of temporal luminance variations in a pair of uniform 17° fields with different temporal modulations. In general, discomfort increased with deviations from natural amplitude spectra, particularly those with excess energy at medium frequencies or biased toward sharper spectra. These ratings of discomfort were also consistent with ratings of how natural the modulations appeared. However, the temporal discomfort judgments were also strongly affected by the phase spectra of the flicker, with fixed vs. random spectra producing very different responses. This was not due to the perceived regularity or predictability of the flicker, but could arise from a number of other potential factors. Our findings suggest that, like spatial patterns, visual discomfort in time-varying patterns depends in part on how similar they are to the amplitude spectra of temporal variations in the natural visual environment, but also point to the critical role of the phase spectrum in the perceived discomfort of flicker.

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1. Introduction

Visual discomfort or stress refers to an unpleasant viewing experience, and represents a widely-studied perceptual judgment that is intuitive to observers and can be reliably measured (e.g., Wilkins, 1995, 2016). Flickering lights are known to induce discomfort and can even induce seizures in observers with photosensitive epilepsy, and many anecdotal examples have been reported in the popular media. For example, in the 1980s, a young male had a seizure when viewing a U.S. TV show, “Captain Powers”, which included frequent flashes from shooting guns. In 1993, a TV commercial for “Golden Wonder, Pot Noodle” induced seizures in three viewers when it was first aired in the U.K. This was attributed to the rapidly flashing lights used in the advertisement. On

the evening of December 16, 1997, when a popular TV cartoon called “Pocket Monster” was broadcast in Japan, many viewers complained of headache and feeling unwell, and more than 700 viewers went to hospital, most as a result of seizures. The critical scene that induced seizures was composed of rapidly alternating red/blue light (Fisher, Harding, Erba, Barkley, & Wilkins, 2005; Takahashi & Tsukahara, 1998). Aversive flicker can also be produced by conventional lighting. For example, lamps that flicker with frequencies of 100 Hz or 120 Hz may appear steady and continuous because the flicker is above the critical flicker fusion threshold, but may nevertheless contribute to headaches and migraine (Poplawski & Miller, 2013; Wilkins, Nimmo-Smith, Slater, & Bedocs, 1989). An understanding of the temporal characteristics of visual discomfort is therefore important from both scientific and practical viewpoints (Wilkins, 2016). The aim of this study is to clarify the underlying factors of visual discomfort caused by time-varying patterns.

Visual discomfort also can be induced by spatial patterns. In the spatial domain, there is a burgeoning literature on visual

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discomfort, which is closely allied to photophobia, and exacerbated in migraine: striped patterns (Chatrrian, Lettich, Miller, & Green, 1970; Marcus & Soso, 1989; Wilkins, 1995; Wilkins et al., 1984), filtered noise (Fernandez & Wilkins, 2008; Juricevic, Land, Wilkins, & Webster, 2010; O'Hare & Hibbard, 2011), blurred images (O'Hare & Hibbard, 2013), certain artistic styles (Fernandez & Wilkins, 2008), and images comprising clusters of objects (Cole & Wilkins, 2013) have all been reported to produce seizures, discomfort or aversion. Discomfort from images could arise from many sources, including properties of the stimulus (e.g., gloomy illumination or glare) or properties of the observer (e.g., accommodative stress or lag, photophobia, or cognitive factors). However, the uncomfortable images identified in the studies above shared in common that they all tended to deviate from the statistics of typical natural scenes, and this is the aspect of discomfort that we focus on in the present work. Natural images have a characteristic redundant structure in that the luminances of nearby points tend to be correlated. This redundancy is captured by the amplitude spectrum in the frequency domain, which typically exhibits an inverse relationship between amplitude and spatial frequency ($1/\text{frequency}$, $1/f$), so that a plot of log amplitude versus log spatial frequency has a slope of -1 (Burton & Moorhead, 1987; Field, 1987; Tolhurst, Tadmour, & Chao, 1992). Note that this pattern is also a characteristic of simple edges such as a square wave, in which the contrast of the harmonics is inversely related to their frequency. Visual processing is assumed to be optimized for encoding images with this $1/f$ spatial structure (Atick, 1990; Atick & Redlich, 1992; Barlow, 1981; Field, 1987), to produce a more efficient and sparse cortical response (Lennie, 2003; Olshausen & Field, 2004). The discomfort from unnatural images might therefore result because they lead to inefficient coding or overstimulation (Fernandez & Wilkins, 2008; Juricevic et al., 2010). Consistent with this, Hibbard and O'Hare (2015) and Penacchio, Otazu, Wilkins, and Harris (2015) used computational models of primary visual cortex (V1) and showed that uncomfortable images which do not contain the $1/f$ structure lead to a non-sparse distribution of neural firing.

Fernandez and Wilkins (2008) also reported that ratings of discomfort correlated with excessive contrast energy relative to $1/f$ at medium spatial frequencies of around $3\text{ c}/^\circ$, i.e., at spatial frequencies at which the visual system is generally most sensitive (Campbell & Robson, 1968). They further found that discomfort ratings were higher for noise patterns filtered to increase the energy at medium frequencies than for those patterns filtered to decrease the energy at medium frequencies, whereas exchanging the phase spectra of comfortable and uncomfortable images had no effect on the ratings. O'Hare and Hibbard (2011) also used filtered noise patterns and showed that excessive contrast energy at medium frequencies determined discomfort ratings. These findings suggest that in addition to being unnatural, an important characteristic that induces visual discomfort is relatively high contrast energy at medium spatial frequencies. Indeed, works of abstract art and images of tiny holes that were empirically known to appear uncomfortable have this spectral feature (Cole & Wilkins, 2013; Fernandez & Wilkins, 2008).

In this study, we examined whether similar spectral properties are related to visual discomfort in the temporal domain, using lights that vary in luminance. A number of previous studies have examined the effects of temporal frequency on discomfort and epileptogenic responses (Harding & Harding, 1999; Harding & Jeavons, 1994; Lin, Hsieh, Chang, & Chen, 2014; Wilkins, 1995). These have again shown that the most aversive frequencies tend to be in the range the visual system is most sensitive to, consistent with overstimulation (Kelly, 1979). However, most of these studies have focused on single frequencies, and thus it remains uncertain how discomfort is related to the temporal statistics of the natural

visual environment. Like spatial variations, variations in time also tend to change gradually and thus are redundant (e.g., Snow, Coen-Cagli, & Schwartz, 2016). Moreover, these correlations may parallel spatial statistics in showing a characteristic $1/f$ structure (Dong & Atick, 1995; van Hateren & van der Schaaf, 1996). However, the temporal statistics of natural stimulation are further affected by the sampling of eye and head movements, which are not $1/f$ (Wilkins, 2016). Moreover, temporal and spatial variations may be encoded in different ways by the visual system, for example with regard to the number and bandwidth of the mechanisms sensitive to different temporal scales (Watson, 1986). Thus the extent to which temporal and spatial deviations from natural spectra might behave in similar ways with regard to discomfort remains uncertain. To assess this, we compared discomfort judgments for flickering stimuli that were manipulated to vary both their amplitude and phase spectra relative to canonical $1/f$ spectra.

2. Experiment 1: Discomfort and biases in medium temporal frequencies

As noted, Fernandez and Wilkins (2008) found that spatial images that were rated as uncomfortable tended to have excess energy at medium spatial frequencies. In the first experiment our aim was to test for similar relationships in the temporal domain. To explore purely temporal variations, we measured discomfort for uniform fields flickered with different phase and amplitude spectra, using a two-alternative forced-choice (2AFC) task. The 2AFC method is suitable for an assessment of relative discomfort or pleasantness of viewing (O'Hare & Hibbard, 2013). In the spatial domain, both relative pleasantness in 2AFC and rated pleasantness on a Likert scale were directly compared as a function of spatial frequency, thereby revealing that the results were closely comparable and related to perceptual distortions, headaches, and discomfort (Wilkins et al., 1984).

While the sensitivity to flicker is highest at approximately 8 Hz when the field size is as small as 2° , the peak shifts to around 15 Hz when the size is increased to 17° (de Lange Dzn, 1958; Kelly, 1961). Lin et al. (2014) used an LED display with the size of $18^\circ \times 15^\circ$ and confirmed that 15 Hz appears most uncomfortable. In Experiment 1, we used a 17° flickering field and increased or decreased the amplitude within a 2-octave band centered at 15 Hz, using a methodology similar to that described by Fernandez and Wilkins (2008).

2.1. Methods

2.1.1. Participants

Fourteen individuals (four male and 10 female) with normal or corrected-to-normal vision participated in Experiment 1 (average age = 25.6 years, range 20–34 years). All were naive to the purpose of the experiment. The study followed protocols approved by the Institutional Research Board of University of Nevada and was conducted according to the Declaration of Helsinki. All participants provided written informed consent before the study began.

2.1.2. Apparatus

All stimuli were displayed on a 22-inch NEC MultiSync FP2141SB monitor at a resolution of 1024×768 pixels with a refresh rate of 120 Hz, and controlled by a Cambridge Research System ViSaGe MKII. The monitor output was gamma corrected based on calibrations with a PR655 spectroradiometer. Participants observed the display binocularly in an otherwise dark room from a distance of 57 cm, with their position maintained with the aid of a headrest.

2.1.3. Stimuli

All stimuli were presented in a pair of uniform 17° fields, shown on a gray background with the same chromaticity (CIE 1931; $x = 0.28$, $y = 0.30$) and time-averaged luminance (44 cd/m²). The luminances of the flickering fields were varied according to waveforms obtained by summing the harmonics of a square wave (1st, 3rd, 5th, . . . , 59th) or sawtooth (1st, 2nd, 3rd, . . . , 60th). The fundamental frequency was set at 1 Hz; the highest harmonic frequency was 59 Hz or 60 Hz, and thus close to the limit of temporal resolution (Kelly, 1961). Fig. 1 shows examples of the waveforms and the amplitude spectra. The phase of each harmonic component was fixed at 0° to produce a square wave or sawtooth modulation (fixed phase spectrum), or was randomized from 0° to 360° (random phase spectrum); the random waveforms had the same fundamental and harmonics as a sawtooth. The amplitude spectrum was either fixed at 1/ f , or locally increased or decreased by filtering the spectrum with a raised cosine filter (Fernandez & Wilkins, 2008; Hou, Lesmes, Bex, Dorr, & Lu, 2015) with a peak at 15 Hz and a full bandwidth at half height of 2 octaves. The filter was symmetric in log frequency space. After filtering, the luminance contrast was normalized so that all stimuli had the same root mean square (RMS) contrast of 0.1.

As noted, the stimuli were presented at the monitor refresh rate of 120 Hz. For the random phase waveforms, this could introduce spurious low-frequency modulations for the higher stimulus frequencies owing to under-sampling. However, we confirmed that this sampling rate had negligible effects on the resulting waveforms (by comparing the waveforms sampled at 120 Hz versus 1200 Hz).

Three possible pairs of stimuli with different amplitude spectra were created for each of the phase spectra, and were simultaneously presented to the right and left visual fields. The spatial dis-

tance between the centers of two fields was 20°. Observers judged the fields while fixating a central white dot with a radius of 0.25° at the center of the screen.

2.1.4. Procedure

Each trial began with a 1-s presentation of the fixation dot, followed by the stimulus pair displayed for 5 s. The left versus right position of the two stimuli in the pair was randomized for each trial. Participants were asked to continuously view the fixation dot throughout the trial and to indicate which of the two stimuli appeared more uncomfortable by pressing the appropriate arrow key. After the participants responded, an inter-trial interval with a uniform screen was shown for 1 s before the next trial began. Each participant completed a session consisting of 90 trials: 10 trials for each of the three pairs of amplitude spectra for each of the three phase spectra, which were presented in random order. For the random waveforms the phase of the harmonics was randomized on each trial.

2.2. Results

Relative discomfort scores were transformed based on Thurstone's law of comparative judgment (Thurstone, 1927; Tsukida & Gupta, 2011). For each stimulus, we counted the number of times it was judged more comfortable than its partner in the paired comparison task. A count matrix C is expressed as

$$C = \begin{cases} \text{times option } i \text{ preferred over option } j & \text{if } i \neq j \\ 0 & \text{if } i = j. \end{cases} \quad (1)$$

In Experiment 1, participants judged 10 trials for each comparison: therefore, the minimum and the maximum are 0 and 10, respectively. These raw scores were then converted into proportions of the maximum possible score so that they ranged from 0 to 1. Z-scores for proportions were then calculated using the inverse of the standard normal cumulative distribution function:

$$\hat{\mu}_{AB} = \phi^{-1} \left(\frac{C_{AB}}{C_{AB} + C_{BA}} \right), \quad (2)$$

where ϕ^{-1} is the inverse of the standard normal cumulative distribution function, and where $\hat{\mu}_{AB}$ is the z-score of the proportions that A is judged more uncomfortable than the partner B. To avoid z-scores of infinity, the counts of 0 and 10 were replaced with the values of 0.5 and 9.5 before calculating proportions (Tsukida & Gupta, 2011). The final form of the discomfort score μ for a set of m stimuli was then given by the mean of the z-scores in comparisons between each stimulus and the others:

$$\mu_j = \sum_{i=1}^m \frac{\hat{\mu}_{ij}}{m}. \quad (3)$$

These values were used for the subsequent analysis.

Fig. 2 shows the averaged and individual data for 14 participants at each phase spectrum. The discomfort score is plotted as a function of the amplitude bias. Stimuli with the fixed phase of square wave or sawtooth, were judged as most comfortable when the amplitude spectrum was set to 1/ f , and thus the discomfort score was increased not only for higher-biased amplitude but also for the lower-biased amplitude. In contrast, for the stimuli with random phase, the relative discomfort monotonically increased with an increase in the amplitude at medium frequencies. A repeated-measures two-way ANOVA followed by Tukey's posthoc test for multiple comparisons was conducted. The generalized $\eta^2(\eta^2_c)$, which is suggested for analysis of repeated-measures designs (Bakeman, 2005; Olejnik & Algina, 2003), was used to estimate the effect size and interpreted according to Cohen's recommendation of 0.02 for a small effect, 0.13 for a medium

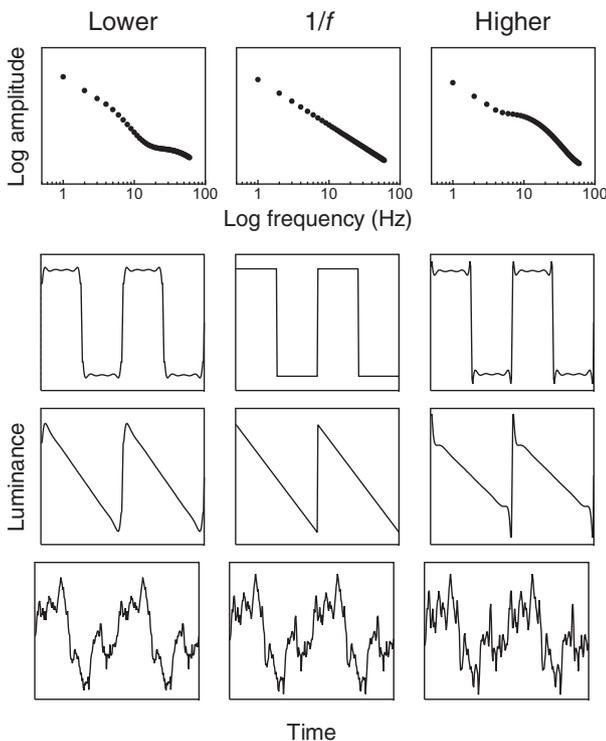


Fig. 1. Schematic examples of the amplitude spectra and waveforms to produce lower (left) or higher (right) amplitude biases at medium frequencies relative to 1/ f (center). The amplitude is plotted as a function of the frequency on log-log axes (first row). The corresponding temporal waveforms are shown for the filtered spectra for square (second row), sawtooth (third row), or random (fourth row).

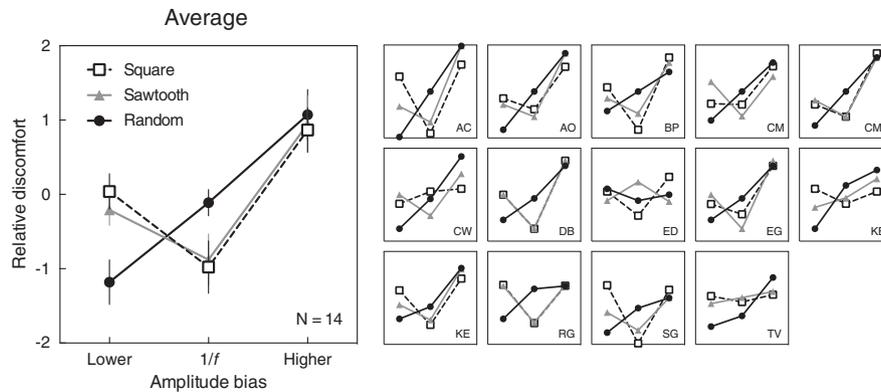


Fig. 2. Averaged and individual discomfort ratings for the 14 participants in Experiment 1. The relative discomfort score is plotted as a function of the amplitude bias. Each curve represents data for the different phase spectra (square, sawtooth, and random). Error bars in the graph of averaged data represent 95% confidence interval (CI).

effect, and 0.26 for a large effect (Cohen, 1988). The main effect of amplitude bias was significant ($F(2, 26) = 55.79$, $p < 0.0001$, $\eta^2_G = 0.67$), whereas that of phase spectrum was not significant ($F(2, 26) = 1.49$, *ns*). The interaction between amplitude bias and phase spectrum was significant ($F(4, 52) = 17.49$, $p < 0.0001$, $\eta^2_G = 0.37$). The Tukey's test revealed significant differences in the discomfort scores among the three amplitude biases for each phase spectrum of the square wave ($q_s \geq 6.06$, $ps < 0.001$), sawtooth ($q_s \geq 4.92$, $ps < 0.01$), and random waveforms ($q_s \geq 7.84$, $ps < 0.0001$).

2.3. Discussion

For the flicker with the fixed phase spectra of a square wave or sawtooth, the discomfort scores increased when the amplitude spectra deviated from $1/f$ by either increasing or reducing energy at medium frequencies. Thus the ratings cannot be accounted for differences in the perceived contrast of the patterns (which again were equated for constant RMS contrast), and instead suggest that discomfort in part depends on how much the waveforms differed from a $1/f$ spectrum (Juricevic et al., 2010; O'Hare & Hibbard, 2013). Moreover, there was a consistent asymmetry in the ratings, with more discomfort for the higher amplitude biases in the waveforms. This parallels the results of Fernandez and Wilkins (2008) in the spatial domain, and is consistent with an account in which the high-biased patterns are more uncomfortable because they produce greater stimulation. On the other hand, the pattern obtained for the random waveforms was very different – with the level of discomfort decreasing with the amplitude of the medium frequencies, regardless of the amplitude that was most natural. Thus the two types of waveforms (fixed or random phase) appeared to elicit different responses, indicating that discomfort depended on properties of both the amplitude spectrum and the phase spectrum.

3. Experiment 2: Discomfort and biases in the slope of the amplitude spectrum

In Experiment 2, we examined the effects of a second form of deviation from naturalistic ($1/f$) spectra on discomfort, in which the overall slope of the spectrum was varied to produce steeper (slope < -1) or shallower (slope > -1) falloff of contrast with increasing frequency. These slope changes have been studied extensively to examine how well visual coding might be matched to $1/f$ spectra (e.g., Hansen & Hesfs, 2006; Johnson, Richard, Hansen, & Ellemberg, 2011; Knill, Field, & Kersten, 1990; Tadmor & Tolhurst, 1994), and as a stimulus for probing blur perception

and adaptation (Elliott, Georgeson, & Webster, 2011; Webster, Georgeson, & Webster, 2002; Webster & Marcos, 2017). Specifically, steeper slopes typically appear blurred, while shallower slopes appear too sharp, and these percepts occur both within the spatial and temporal domains (Bilson, Mizokami, & Webster, 2005). Juricevic et al. (2010) previously showed that spatial images (Mondrians or filtered noise) were rated most comfortable when their amplitude spectrum was $1/f$, with discomfort increasing for both blurred and sharpened slopes. In the next experiment we again tested for parallel effects on discomfort for temporal patterns.

3.1. Methods

3.1.1. Participants

Ten individuals (three male and seven female) with normal or corrected-to-normal vision participated in Experiment 2 (average age = 27.1 years, range 23–31 years). Seven were new observers, while three had participated in Experiment 1.

3.1.2. Stimuli

The waveforms were again composed of the harmonics of a square wave with either fixed or random phase, but were filtered by scaling the amplitudes of the components by f^s , where the exponent s corresponded to the slope change on a log-log plot (Fig. 3). The value of s was set to -0.4 , -0.2 , 0 , 0.2 , or 0.4 , relative to the original amplitude spectrum of -1 . Thus the absolute slopes corresponded to -1.4 , -1.2 , -1 , -0.8 , and -0.6 . As noted, a steeper slope (< -1) decreased the relative amplitude of higher temporal frequencies resulting in smoothed or blurred transitions, whereas shallower slopes (> -1) boosted the higher frequencies resulting in sharpened transitions. As in the previous experiment, contrast was normalized after filtering so that all stimuli had a constant RMS contrast of 0.1. Ten possible pairs of stimuli with different amplitude spectra were created for each phase spectrum.

3.1.3. Procedure

The procedure was the same as in Experiment 1, where observers judged which stimulus in the pair appeared more comfortable. Each participant completed a session consisting of 200 trials: 10 trials for each of the 10 pairs of amplitude spectra for each of the two phase spectra, which were presented in random order. For the random waveforms the phase of each harmonic component was again randomized for each trial.

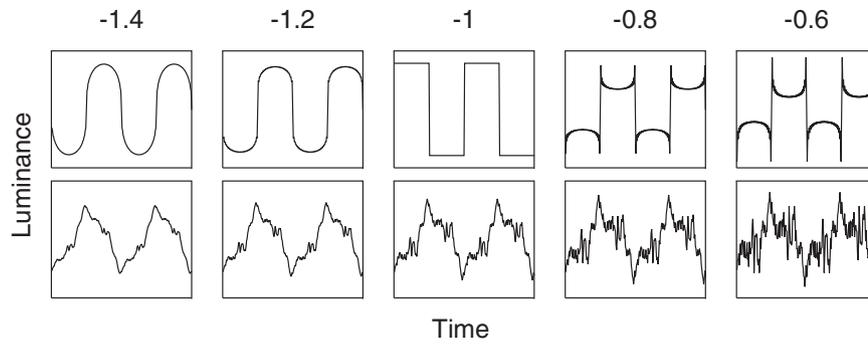


Fig. 3. Schematic example of the waveform of the square wave (top) or random waveform (bottom). The slope of the amplitude spectrum was -1.4 , -1.2 , -1 , -0.8 , or -0.6 , from left to right. The luminance of the waveform is plotted as a function of time.

3.2. Results

Discomfort scores were calculated as in Experiment 1. Fig. 4 shows the averaged and individual scores for the 10 participants, with the score plotted as a function of the slope of the amplitude spectrum. Discomfort for the square wave stimuli was least for a slope of -1 , again increasing for both steeper and shallower slopes. In contrast, discomfort from the modulations with random phase instead increased monotonically as the slope became shallower. A repeated-measures two-way ANOVA followed by Tukey’s post-hoc test for multiple comparisons was conducted. The main effect of the slope was significant ($F(4, 36) = 154.6$, $p < 0.0001$, $\eta^2_G = 0.91$), whereas that of phase spectrum was not significant ($F(1, 9) = 0.005$, *ns*). The interaction between the slope and phase spectrum was significant ($F(4, 36) = 29.11$, $p < 0.0001$, $\eta^2_G = 0.58$). The Tukey’s test revealed significant differences in the discomfort scores among the five slopes ($qs \geq 4.40$, $ps < 0.05$), except between -1 and -1.2 ($q = 3.07$, *ns*) and between -1.2 and -1.4 ($q = 1.33$, *ns*) for the square wave modulations.

3.3. Discussion

The slope changes in the amplitude spectrum parallel many features of the discomfort ratings when medium temporal frequencies were manipulated (Experiment 1). Specifically, for both the fixed and random-phase stimulus, discomfort was greatest for the shallowest slopes. The higher discomfort ratings for sharper stimuli is consistent with the idea that excessive contrast energy at medium frequencies determined discomfort ratings, because shallower slopes increased the medium frequencies as well as high

frequencies. However, the present results again point to clear differences between the random and fixed phases, with the square wave ratings lowest for $1/f$ spectra while the random phase ratings decreased monotonically with steeper slopes. This again suggests that both the amplitude and the phase spectrum impact the perceived discomfort of the patterns.

4. Experiment 3: Amplitude biases and judgments of naturalness

An aim of the previous experiments was to assess whether images with unnatural amplitude spectra appear more uncomfortable. The phase effects we observed in both cases suggest that our objective definition of natural ($1/f$ spectrum) could not on its own account for the results. However, how natural the stimuli appeared subjectively to the observers was unclear. To examine this, in the next experiment we used the same stimuli but asked observers to make a different judgment to directly evaluate naturalness.

4.1. Methods

4.1.1. Participants

Eleven individuals (5 male and 6 female) with normal or corrected-to-normal vision participated in Experiment 3 (average age = 22.6 years, range 21–26 years). All were new observers and naïve to the purpose of the experiment.

4.1.2. Stimuli and procedure

The stimuli and procedure were identical to Experiment 2, except that participants were asked to indicate which of the two

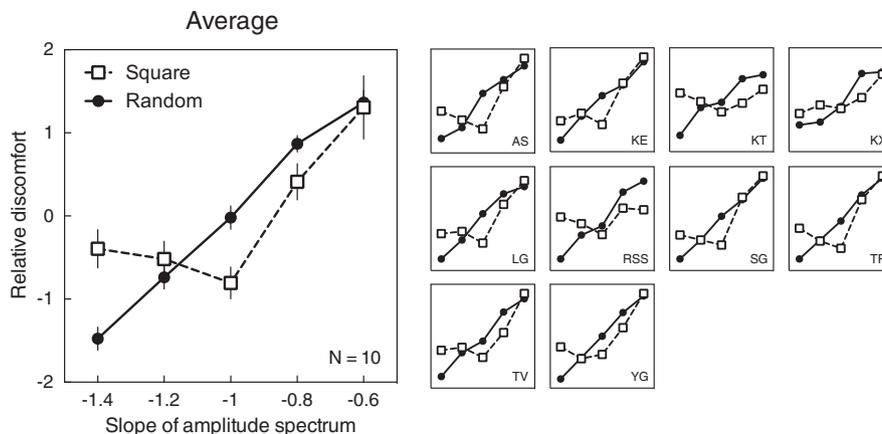


Fig. 4. Averaged and individual data for the 10 participants in Experiment 2. The relative discomfort score is plotted as a function of the slope of the amplitude spectrum. The slope of -1 corresponds to $1/f$. The two curves represent ratings for the different phases (square wave or random). Error bars in the graph of averaged data represent 95% CI.

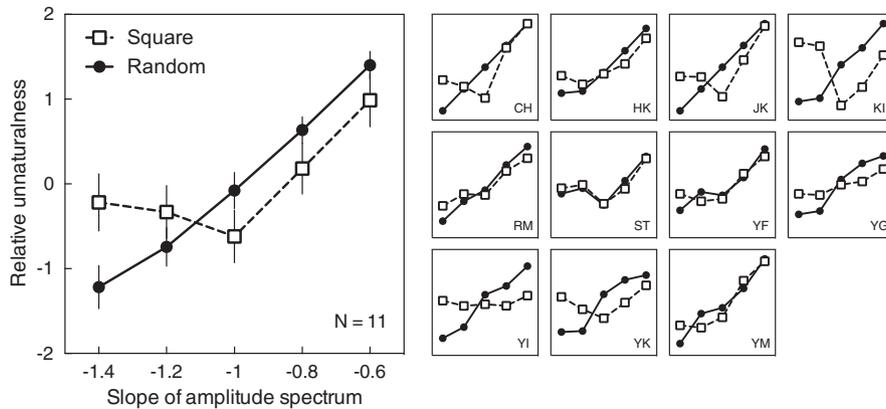


Fig. 5. Averaged and individual data for the 11 participants in Experiment 3. The relative unnaturalness score is plotted as a function of the slope of the amplitude spectrum. The slope of -1 corresponds to $1/f$. The two curves represent ratings for the different phases (square wave or random). Error bars in the graph of averaged data represent 95% CI.

stimuli appeared more unnatural by pressing the appropriate arrow key.

4.2. Results

Unnaturalness scores were calculated in the same manner as discomfort scores described in Experiment 1. Fig. 5 shows the averaged and individual scores for the 11 participants, with the score plotted as a function of the slope of the amplitude spectrum. The relative unnaturalness for the square wave stimuli was least at the slope of -1 , increasing for both steeper and shallower slopes, whereas unnaturalness in the modulations with random phase monotonically increased as the slope became shallower. A repeated-measures two-way ANOVA followed by Tukey's posthoc test for multiple comparisons was conducted. The main effect of the slope was significant ($F(4, 40) = 65.97, p < 0.0001, \eta^2_G = 0.78$), whereas that of phase spectrum was not significant ($F(1, 10) = 0.44, ns$). The interaction between the slope and phase spectrum was significant ($F(4, 40) = 13.83, p < 0.0001, \eta^2_G = 0.39$). The Tukey's test revealed significant differences in the unnaturalness scores among the five slopes ($qs \geq 5.15, ps < 0.01$), except among $-0.8, -1.2,$ and -1.4 ($qs \leq 3.97, ns$) and among $-1, -1.2,$ and -1.4 ($qs \leq 3.12, ns$) for the square wave modulation, and between -1.2 and -1.4 ($q = 3.68, ns$) for the random wave modulations.

4.3. Discussion

The ratings for perceived naturalness closely paralleled the discomfort ratings of Experiment 2 (Fig. 4), for both the square wave and random phases. This supports the conjecture that the stimuli that appeared unnatural were more likely to appear uncomfortable, even if this appearance was not captured by a single property like the $1/f$ spectrum. As with discomfort, the perceived naturalness again depended strongly on the phase spectrum. In the next experiment, we examined these phase effects more closely, by comparing discomfort in modulations with the same amplitude but different phases.

5. Experiment 4: Discomfort and stimulus phase spectrum

In the preceding experiments, observers always compared modulations that had the same phase but different amplitude spectra. The differences found for random versus fixed phases showed that phase contributed to the judgments, but leaves unanswered how uncomfortable different phases appeared relative to each other. To examine this, in Experiment 4 we held the amplitude spectrum

of all of the stimuli constant, at $1/f$, and instead varied the phase of the harmonics.

5.1. Methods

5.1.1. Stimuli

In this case all stimuli had the odd harmonics and $1/f$ amplitude spectrum for the square wave stimulus, but the phases of the components were shifted equally in steps of 30° ($0^\circ, 30^\circ, 60^\circ,$ or 90°) or were randomized. The fixed phase shifts alter the stimulus from a square wave to symmetric (90°) or asymmetric variants of triangular waves (Fig. 6). All other stimulus details were the same as those in Experiment 1. Ten possible pairs of stimuli with different phase spectra were created.

5.1.2. Procedures

The procedure was the same as in Experiment 1, with each participant completing a session consisting of 100 trials: 10 trials for each of the 10 pairs of phase spectra, which were presented in random order. The same individuals that performed Experiment 1 participated in Experiment 4.

5.2. Results

Discomfort scores were again calculated in the manner described previously. Fig. 7 shows the averaged and individual scores for the 14 participants, with the score plotted as a function of the phase spectrum. The stimuli with a random phase spectrum were clearly judged as more uncomfortable than all of the fixed phase spectra, which appeared largely unaffected by the specific phase angle ($0^\circ, 30^\circ, 60^\circ,$ or 90°). A repeated-measures one-way ANOVA followed by Tukey's posthoc test was conducted for multiple comparisons. The main effect of phase spectrum was significant ($F(4, 52) = 48.64, p < 0.0001, \eta^2_G = 0.79$). The Tukey's test revealed significant differences in the discomfort scores between the stimuli with random and each fixed phase spectrum ($qs \geq 16.69, ps < 0.0001$) while no significant differences in the discomfort scores among the stimuli with the fixed phase spectrum ($qs \leq 4.08, ns$).

5.3. Discussion

The discomfort ratings in the patterns of flicker showed pronounced effects of the phase spectrum, a result which is potentially different from the effects found for spatial variations (Fernandez & Wilkins, 2008). Surprisingly however, this difference was confined

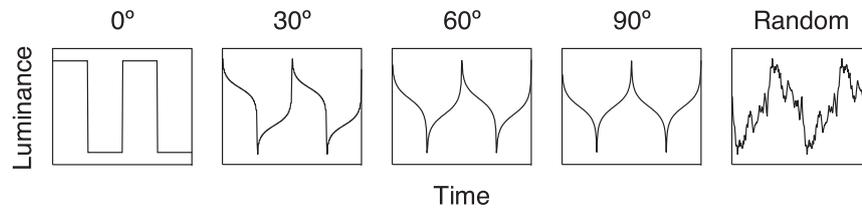


Fig. 6. Schematic examples of the waveform for phases of 0°, 30°, 60°, 90°, or random, from left to right. The luminance is plotted as a function of the time.

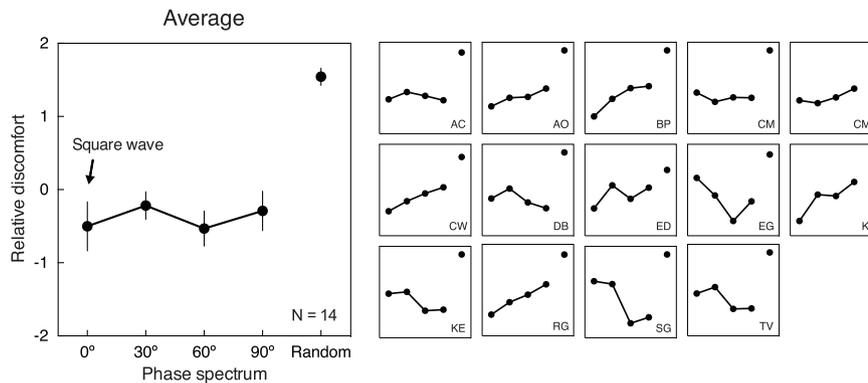


Fig. 7. Averaged and individual data for the 14 participants in Experiment 4. The relative discomfort score is plotted as a function of the phase spectrum. The spectrum of 0° corresponds with $1/f$. Error bars in the graph of averaged data represent 95% CI.

to comparisons between fixed versus random phases. For the different fixed phases, there was instead not a measurable difference in the relative ratings. This is despite the fact that the fixed phase shifts produced dramatically different waveforms with salient differences in appearance. In any case, the results again confirm a strong general effect of the phase spectrum on discomfort ratings: the random phase pattern appeared more uncomfortable than the fixed phase patterns. One possible explanation is that the random pattern is by definition less predictable than the repeating cycles generated by the fixed phase spectra. This unpredictability could itself potentially appear less comfortable. This possibility was assessed in the final experiment.

6. Experiment 5: Discomfort and stimulus regularity

To explore the effects of regularity of the flicker, we compared the ratings for a square wave, jittered square wave, and random phase patterns. The jittered square wave was created by using a square wave pattern, but randomly varying the timing between the temporal edges. This preserved the luminance profile of the edges themselves, but removed the predictability of the flicker.

6.1. Methods

6.1.1. Stimuli

Square wave and random phase stimuli that had the odd harmonics and $1/f$ amplitude spectrum were again used. A square wave stimulus with jitter was generated by randomly varying the onset of the luminance change of a standard square wave (Fig. 8). The range of jitter values was ± 0.2 s of the nominal period (1 s). The amplitude spectrum remained similar to $1/f$ on average. All other stimulus details were same as those in Experiment 1. Settings were collected for the same 11 observers who participated in Experiment 3.

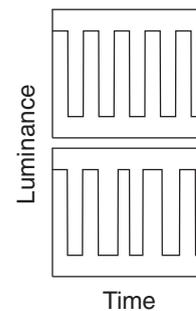


Fig. 8. Schematic examples of the waveform for standard square waves (top) and jittered ones (below). The luminance is plotted as a function of the time.

6.1.2. Procedure

The procedure was the same as in Experiment 1, with each participant completing a session consisting of 30 trials: 10 trials for each of the three pairs of waveforms, which were presented in random order. For the jittered square waves the onset of the luminance change was randomly varied for each trial.

6.2. Results

Discomfort scores were calculated in the same manner described previously. Fig. 9 shows the averaged and individual scores for the 11 participants, with the score plotted as a function of the waveforms. The stimuli based on random waves were again judged as more uncomfortable than jittered square waves, which appeared as comfortable as standard square waves. A repeated-measures one-way ANOVA followed by Tukey's posthoc test was conducted for multiple comparisons. The main effect of waveform was significant ($F(2, 20) = 190.5, p < 0.0001, \eta_c^2 = 0.95$). The Tukey's test revealed significant differences in the discomfort scores between the stimuli based on random and jittered/standard square

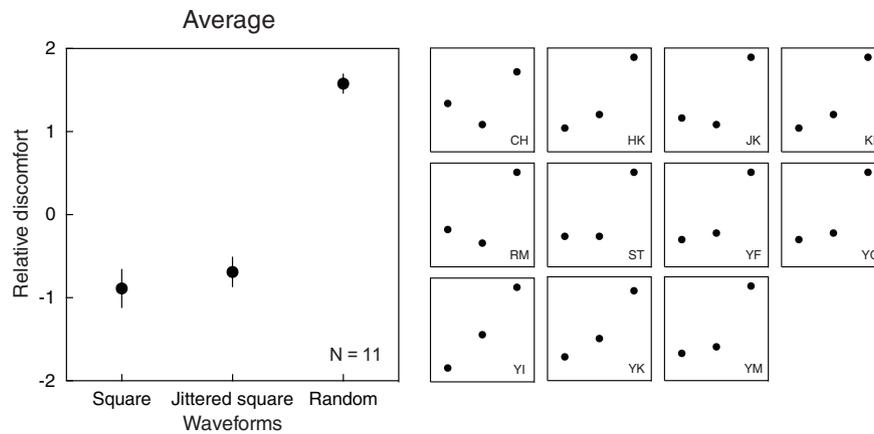


Fig. 9. Averaged and individual data for the 11 participants in Experiment 5. The relative discomfort score is plotted as a function of the waveforms. Error bars in the graph of averaged data represent 95% CI.

waves ($q_s \geq 22.83$, $p_s < 0.0001$) while no significant differences in the discomfort scores between the stimuli based on the jittered and standard square waves ($q \leq 2.02$, *ns*).

6.3. Discussion

As shown in Experiment 5, the discomfort ratings for random phase patterns were prominent compared with the square wave. Further, a difference was not observed between the jittered and standard square waves in spite of the salient differences in the timing of the luminance transitions. The results suggest that the perceived predictability in the luminance-varying patterns is not a critical factor for the discomfort ratings. It should be noted that jittering the fundamental does alter the amplitude spectrum and therefore introduces additional random frequency components. However, the results were unchanged by jittering itself, indicating that this did not have a significant effect on discomfort ratings.

7. General discussion

In this study, we explored the effects of different temporal waveforms on judgments of visual discomfort, focusing on the “profile” of the patterns rather than simpler features such as the individual frequency or physical intensity. It should be emphasized that the patterns themselves may have differed only mildly in how aversive or unpleasant they might have appeared, and our relative settings do not address this. Moreover, for such stimuli in general it is an unresolved question how observers’ judgments of discomfort might be related to an alternative judgment such as stimulus preference. However, as we noted, discomfort has been found across a wide array of studies to be a robust perceptual attribute of visual stimuli, and one that can be highly aversive in some contexts and individuals (Wilkins, 1995). Further, our study focused on a class of stimuli that has been shown to give rise to discomfort – luminance flicker. It should also be re-emphasized that there are many different potential sources and causes of visual discomfort. Our study also focused on only one of these – to examine the effects of the specific pattern of the flicker.

In the spatial domain, deviations from the natural ($1/f$) amplitude spectra or excessive contrast energy at medium spatial frequencies can evoke discomfort. Here, we investigated whether analogous effects occur in the temporal domain. To summarize, our results showed that the discomfort scores for flicker were affected by the amplitude spectrum, but also by the phase spectrum. For the flicker with a fixed phase spectrum, the discomfort

scores were consistently lowest for $1/f$ spectra and increased for both steeper and shallower slopes, as well as for both increased and decreased energy at medium temporal frequencies. For the flicker with a random phase spectrum, the discomfort scores were instead consistently lowest for the modulations with the least high-frequency modulation, and thus were lower for blurred stimuli than for $1/f$ stimuli. The pattern of results therefore strongly depended on the phase spectrum. These results argue against a simple explanation of the ratings in terms of how they differ from $1/f$. Notably, however, they remained consistent with observers’ subjective ratings of how naturalistic the different temporal patterns appeared.

When the phase was varied among modulations with the same amplitude spectrum, observers strongly preferred the fixed-phase stimuli over the random modulations. These phase effects again show that the actual pattern of the waveform played an important role in the observers’ judgments, but what was it about the phase that mattered? The results for the temporally jittered square wave showed that the effect was not due to the regularity or predictability of the luminance changes. However, there are number of other important differences between the fixed and random patterns that could potentially impact discomfort. For example, for fixed phase, note that the patterns always represent different temporal gradients corresponding to simple “edges” in time. These edges correspond to the carrier frequency, while the higher harmonics determine the profile (e.g., blurred or sharp) of the gradients. It is possible in this case that discomfort is determined by how natural these gradients appear. For example, a square-wave edge might correspond to temporal changes involving occlusions or from saccades. Blurring or over-sharpening this transition may produce an unnatural transition, increasing discomfort. Indeed, those stimuli can appear unnatural (Fig. 5). In the spatial domain, O’Hare and Hibbard (2013) suggested that an increase in microfluctuations caused by impoverished feedback for the accommodative response is a direct source of discomfort for blurred images. However, in our experiment, we obtained analogous effects for temporal blur in uniform fields, for which accommodation seems less of a factor. Thus this may point to other more central bases for the percepts.

For the random phase spectra, again the discomfort monotonically increased the less “blurred” the stimulus was. An important difference is that in this random case the modulation does not have consistent repeating edges. But why should that lead to a different pattern of the effects of the amplitude spectrum on discomfort? We consider several possibilities. First, in spatial patterns like a square wave, there is evidence that sensitivity to the higher harmonics can be depressed. For example, less adaptation occurs for

higher harmonics when they are shown in the presence of the fundamental (Mizokami, Paras, & Webster, 2004; Nachmias, Sansbury, Vassilev, & Weber, 1973; Tolhurst, 1972; Tolhurst & Barfield, 1978). However, this suppression is in part released when the harmonics are randomized or move freely relative to the fundamental (Klein & Stromeyer, 1980). A similar effect may occur in the temporal domain. By this account, the random patterns were more uncomfortable because the energy at the higher frequencies was more salient or potentially released from this suppression. Blurred random modulations would include less of this energy and thus appear more comfortable (though we note that a corresponding pattern was not found for spatial filtered noise; Juricevic et al., 2010). A second possibility is that random modulations effectively contain more high-frequency events. As Fig. 1 illustrates, the fixed phase spectra had a single prominent transition at a rate of 1 Hz. However, the random spectra include many local peaks and troughs. If the visual system coded the waveforms nonlinearly in a way that gave extra salience to these local events, then the random modulation might appear to have much more high frequency flicker.

Finally, it is possible that the phase effects reflect higher-level judgments or characteristics of the natural temporal statistics, for example corresponding to different classes of objects or events. As noted, in a three-dimensional world, where both objects and observers move and change their spatial relationships, temporal edges frequently occur as a result of occlusions and gaze shifts. In contrast, random phase modulations could reflect some aspects of the dynamics of objects or material properties, such as biological motion or material flow patterns. For example, Kawabe et al. (2015) used noise patterns and showed that the appearance of liquid-like materials in the luminance-based motion could be recognized with high accuracy and that the smoothness of motion flow was a critical property for liquid perception. They conjectured that the visual system directly and heuristically associates visual appearance with liquids, an abundant material in the natural environment. Blurring the random modulations might produce smoother transitions more typical and thus diagnostic of natural material dynamics. This speculation is supported by the observation that, again unlike the fixed-phase patterns, the subjective naturalness in the random modulations monotonically increased as the blur increased (Fig. 5), and is consistent with the notion that the visual system has heuristic mechanisms for material perception using simple visual features correlated with the physical material profiles in nature (Fleming, 2014; Kawabe et al., 2015; Kawabe, Maruya, & Nishida, 2015; Marlow, Kim, & Anderson, 2012; Motoyoshi, Nishida, Sharan, & Adelson, 2007; Norman, Wiesemann, Norman, Taylor, & Craft, 2007).

As noted in the Introduction, one mechanistic account of visual discomfort is that it arises from overstimulation or increased neural activity (Fernandez & Wilkins, 2008; Hibbard & O'Hare, 2015; Juricevic et al., 2010). This is consistent with the findings that discomfort for single spatial or temporal frequencies is greatest for the frequencies that the visual system is most sensitive to. For example, Harding and Harding (1999) showed that the percentage of photosensitive observers with a photoparoxysmal EEG response to flickering lights peaked at medium frequencies of 12–30 Hz. It is also consistent with the findings that higher contrast patterns are more uncomfortable (Haigh, Cooper, & Wilkins, 2015) and the associations between migraine and neural activity in primary visual cortex (Huang, Cooper, Satana, Kaufman, & Cao, 2003). This account would predict that $1/f$ spectra should produce weaker or more efficient neural responses, and as noted this has been predicted in computational models (Hibbard & O'Hare, 2015). Surprisingly however, two recent fMRI studies have instead found stronger BOLD responses for $1/f$ patterns compared to steeper or shallower spectra, albeit for patterns with moderate contrast of

30% (Isherwood, Schira, & Spehar, 2017; Tregillus, Strother, Caplovitz, & Webster, 2014). However, it is generally the case that uncomfortable visual stimuli give a larger BOLD response (Wilkins, 2016). The neural basis for discomfort for our spectra thus remains in question.

Regardless of its basis, it is notable that judgments of discomfort were highly reliable and consistent across the observers, and thus the attribute of discomfort is salient and robust. Moreover, discomfort is an attribute that is relevant to many perceptual domains, and might reflect similar processes and principles. For example, analogous effects are well known for audition. The threshold of discomfort in healthy individuals tends to be lowest near the medium temporal frequencies to which our auditory system is most sensitive (Fletcher & Munson, 1933). Previous studies have also shown that the loudness fluctuations in music, speech, and pitch may exhibit $1/f$ amplitude spectra (Klimontovich & Boon, 1987; Voss & Clarke, 1975, 1978), and it remains a controversial issue whether music containing $1/f$ components is the most pleasant to hear. Warner and Bender (2002) measured the threshold of discomfort across complex stimuli including environmental sounds and showed that an increase in the frequency of the primary spectral peak and the presence of more spectral peaks lowered the discomfort threshold, potentially paralleling some of the properties we observed.

In modern urban life, we are continuously exposed to unnatural and artificial visual stimuli, which can appear uncomfortable and can even induce photosensitive seizures, headache, and migraine (Le et al., 2017). With the development of computer animation techniques and practical applications, such symptoms may occur more frequently. In 2005, the International Organization for Standardization argued that more guidelines on image safety are needed (So & Ujike, 2010). Our findings help contribute to understanding and thus potentially evaluating and developing standards for the dynamics of lighting and animation to reduce the possibility of aversive effects.

8. Conclusions

We found that like spatial patterns, biases from the $1/f$ amplitude spectra increased discomfort. In particular, flicker that has excess contrast at medium temporal frequencies to which the visual system is generally most sensitive led to strong discomfort. These results suggest that deviations from the $1/f$ spectra have corresponding consequences in the temporal and spatial domains. However, our results also show that the amplitude spectrum alone does not fully determine discomfort; variations in the phase spectrum also strongly affected the discomfort judgments. These findings suggest that discomfort may be related to different aspects of temporal dynamics and possibly how these reflect different aspects of the physical world, and have practical implications for artificial stimulus environments, such as visual displays, computer monitors, and television screens.

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