Visual discomfort from flicker: Effects of mean light level and contrast

Sanae Yoshimoto [a, *], Fang Jiang [b], Tatsuto Takeuchi [c], Arnold J. Wilkins [d], Michael A. Webster [b]
[a]Hiroshima University, [b]University of Nevada, Reno, [c]Japan Women's University, [d]University of Essex

[a] Graduate School of Integrated Arts and Sciences, Hiroshima University, Kagamiyama 1-7-1, Higashi-Hiroshima, Hiroshima 739-8521, Japan
[b] Department of Psychology, University of Nevada, Reno, 1664 N. Virginia Street, Reno, Nevada 89557, USA
[c] Department of Psychology, Japan Women's University, Tama-ku Nishi-ikuta 1-1-1, Kawasaki, Kanagawa 214-8565, Japan
[d] Department of Psychology, University of Essex, Wivenhoe Park, Colchester CO4 3SQ, UK
[*] Corresponding author

Author Note:
Sanae Yoshimoto, email: syoshimo@hiroshima-u.ac.jp
Fang Jiang, email: fangj@unr.edu
Tatsuto Takeuchi, email: takeuchi@fc.jwu.ac.jp
Arnold J. Wilkins, email: arnold@essex.ac.uk
Michael A. Webster, email: mwebster@unr.edu

Correspondence:
Sanae Yoshimoto
Hiroshima University
Kagamiyama 1-7-1, Higashi-Hiroshima, Hiroshima 739-8521, Japan
+81-82-422-7111
syoshimo@hiroshima-u.ac.jp

Abstract

Uncomfortable images generally have a particular spatial structure, which deviates from a reciprocal relationship between amplitude and spatial frequency (*f*) in the Fourier domain (1/*f*). Although flickering patterns with similar temporal structure also appear uncomfortable, the discomfort is affected by not only the amplitude spectrum but also the phase spectrum. Here we examined how discomfort from flicker with differing temporal profiles also varies as a function of the mean light level and luminance contrast of the stimulus. Participants were asked to rate discomfort for a 17° flickering uniform field at different light levels from photopic to scotopic. The flicker waveform was varied with a square wave or random phase spectrum and filtered by modulating the slope of the amplitude spectrum relative to 1/*f*. At photopic levels, the 1/*f* square wave flicker appeared most comfortable, whereas the discomfort from the random flicker increased monotonically with shallower amplitude slope. This special status for the 1/*f* square wave condition was limited to photopic light levels. At the lower mesopic or scotopic levels, the effect of phase spectrum on the discomfort was diminished, with both phase spectra showing a monotonic change with the slope of the amplitude spectrum. We show that these changes cannot be accounted for by changes in the effective luminance contrast of the stimuli or by the responses from a linear model based on the temporal impulse responses under different light levels. Meanwhile, discomfort from flicker is robustly correlated with judgments of the perceived naturalness of flicker across different contrasts and mean luminance levels.

Keywords: visual discomfort, flicker, retinal illuminance, contrast, 1/*f* amplitude spectrum

1. Introduction

Some visual patterns can induce adverse effects (e.g., migraine, headache, epileptic seizures) in photosensitive observers and appear uncomfortable for normal observers, inducing so-called visual discomfort (Wilkins, 1995; 2016). Visual discomfort refers not only to clinical responses but also any unpleasant viewing experiences such as visual disturbance, annoyance, and irritation. Many aspects of visual discomfort from images, such as certain geometric patterns (Chatrian et al., 1970; Fernandez & Wilkins, 2008; Juricevic et al., 2010; Marcus & Soso, 1989; O'Hare & Hibbard, 2011, 2013; Wilkins, 1995; Wilkins et al., 1984), artistic paintings (Fernandez & Wilkins, 2008), and natural images containing clusters of small objects (Cole & Wilkins, 2013), have been studied.

Fernandez and Wilkins (2008) asked participants to rate visual discomfort from filtered noise and artistic images. They found that the images with an excess energy at the middle spatial frequencies were rated as more uncomfortable and also showed that the amplitude spectrum rather than phase spectrum determined the discomfort by replacing the phase spectra of uncomfortable images with those of comfortable images. Juricevic et al. (2010) also measured discomfort ratings for filtered noise patterns and showed that the patterns appeared most comfortable when their amplitude fell proportionally as spatial frequency (f) increased ($1/f$ or –1 slope for log amplitude and log frequency). Natural images generally have this $1/f$ spatial structure (Atick, 1990; Atick & Redlich, 1992; Barlow, 1981; Field, 1987; Lennie, 2003; Olshausen & Field, 2004; Párraga, Troscianko, & Tolhurst, 2000; Srinivasan, Laughlin, & Dubs, 1982), and thus the discomfort could reflect a response to stimuli that the visual system does not process efficiently (Wilkins & Hibbard, 2014).

Diffuse flicker and flickering patterns can also induce visual discomfort or seizures (Binnie, Findlay, & Wilkins, 1985; Fisher et al., 2005; Harding & Harding, 2005; Harding & Jeavons, 1994; Lin et al., 2014; Wilkins, 1995; Yoshimoto et al., 2017; 2019). Flickering patterns at temporal frequencies at which humans are most sensitive can produce discomfort in normal observers (Lin et al., 2014) and headaches or seizures in photosensitive observers (Harding & Jeavons, 1994). Yoshimoto et al. (2017) measured discomfort for flickering patterns with different amplitude and phase spectra and showed that the discomfort increased when the temporal structure deviated from $1/f$ amplitude spectrum. Like spatial variations, temporal variations in nature generally have a $1/f$ temporal structure, that is, an amplitude spectrum with reciprocal of temporal frequency (Billock, de Guzman, & Scott Kelso, 2001; Dong & Atick, 1995; Isherwood et al., 2018; van Hateren & van der Schaaf, 1996).

Therefore, it also may be possible to predict discomfort from time varying patterns by their temporal amplitude spectra.

However, Yoshimoto et al. (2017) showed that discomfort from flickering patterns was also strongly influenced by their phase spectra, and thus potentially different from the discomfort from spatial stimuli (Fernandez & Wilkins, 2008). When the phase of each temporal frequency component was fixed at a specific value (e.g., 0° for square wave transitions), reported discomfort was lowest for flicker with a $1/f$ spectrum, paralleling the effects for spatial stimuli. On the other hand, when the phase of the harmonics was randomized, discomfort increased monotonically as the slope of the amplitude spectrum decreased, without a minimum at $1/f$. Thus unlike the spatial domain, in the temporal domain not only the amplitude spectrum but also the phase spectrum may play an important role in visual discomfort.

In this study, we examined two further potential influences on discomfort from flicker: the mean light level and the luminance contrast of the stimulus. Most previous studies of visual discomfort have been conducted with high-contrast stimuli at photopic light levels, at which primarily only the cones operate. However in the natural environment, ambient light levels change by a factor of 10^{11} between day and night (Hood & Finkelstein, 1986; Stockman & Sharpe, 2006), and the range of mesopic and scotopic light levels, at which rods operate, extends over a range of 10^6. Thus, understanding of the characteristic of discomfort induced by visual information at low light levels is important from both scientific and practical viewpoints.

The temporal response of the visual system becomes more sluggish at lower light levels and as vision shifts from photopic to scotopic levels (Burr & Morrone, 1993; Hess, 1990; Robert et al., 1996; Kelly, 1971; Macleod, 1972; Plainis & Murray, 2000; Snowden, Hess, & Waugh, 1995; Swanson et al., 1987; Walkey, Harlow, & Barbur, 2006). The temporal response shifts from band-pass at high light levels to low-pass at low light levels. In many cases, the differences in temporal properties between cone and rod vision can account well for the change in perception of temporally-varying patterns such as moving patterns (Billino, Bremmer, & Gegenfurtner, 2008; Challinor & Mather, 2010; Dawson & Lollo, 1990; Gegenfurtner, Mayser, & Sharpe, 2000; Grossman & Blake, 1999; Hammett et al., 2007; Pritchard & Hammett, 2012; Sheliga et al., 2006; Takeuchi & De Valois, 1997, 2009; Vaziri-Pashkam & Cavanagh, 2008; Yoshimoto, Okajima, & Takeuchi, 2016; Yoshimoto & Takeuchi, 2013). For example, Takeuchi and De Valois (1997, 2009) measured the perceived direction of apparent motion at low light levels and showed that the estimated transmission delays in rod pathways can predict the perceived direction of motion. However, in other cases the perception of moving patterns is invariant with light level (Hess & Zaharia, 2010; Lankheet et al., 2000; Lankheet, van Doorn, & van de Grind, 2002; van de Grind, Koenderink, & van Doorn, 2000). van de Grind et al. (2000) measured the coherent motion threshold and showed that sensitivity was robust across light levels.

Reducing the mean light level from photopic to scotopic decreases the visibility of visual stimuli. Likewise, decreasing the luminance contrast of the stimuli degrades the visibility of stimuli when the mean light level is kept constant. The effect of luminance contrast on temporally-varying patterns, such as visual motion stimuli, has been widely studied. As in the case of the mean light level described above, there are both studies showing that motion perception is invariant with the luminance contrast as well as studies showing that motion perception varies with luminance contrast (Derrington & Goddard, 1989; Edwards, Badcock, & Nishida, 1996; Nakayama & Silverman, 1985; Nishida, Ashida, & Sato, 1997; Ohtani, Ido, & Ejima, 1995; Pantle & Sekuler, 1969; Raymond & Darcangelo, 1990). For example, visual motion measurements, such as the minimum-motion threshold (Nakayama & Silverman, 1985) saturates at low-luminance contrast, whereas other motion phenomena, such as simultaneous motion contrast (Raymond & Darcangelo, 1990) do not saturate at low contrast; thus a higher stimulus contrast induces a stronger perceptual effect. These studies have shown both invariant and variant aspects of visual motion perception when the mean light level or the luminance contrast of the stimulus was varied. We examined how visual discomfort induced by flicker varies (or does not vary) depending on those two parameters.

To explore the underlying mechanisms potentially contributing to discomfort from flicker, we also examined the relationship between discomfort ratings and a number of additional variables. These included the effect of visibility (or effective contrast) of the flicker, the perceived naturalness of the flicker, and the visual responses predicted by a linear model of the temporal contrast response function of the visual system.

2. Methods

2.1. Participants

For the main experiment, eighteen students at Hiroshima University volunteered to participate (mean age = 21.2 years, range 19–28 years, 11 female). Sixteen different students (mean age = 21.1 years, range 20–23 years, 12 female) participated in a separate “naturalness” judgment experiment described below. All had normal or corrected-to-normal vision, and all were naïve to the purpose of the experiment. The study was conducted in accordance with the protocols approved by the Institutional Research and Ethics Committee of Hiroshima University, and with the Declaration of Helsinki. Written informed consent was obtained from each participant before entry into the study.

2.2. Apparatus

Visual stimuli were generated on a PC using MathWorks MATLAB and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997), and presented on a 27-inch EIZO FS2735 liquid crystal display (LCD) at a 8-bit gray-level spatial resolution of 2560 × 1440 pixels. The refresh rate of the display was 120 Hz. The monitor output was gamma-corrected by a Cambridge Research Systems SpectroCAL MKII spectroradiometer. Neutral density filters were used to reduce the mean photopic luminance of the screen over a roughly 5 log unit range from 46.8 to 4.2, 0.35, 0.043, 0.0039, and 0.0006 cd/m^2. The spectral emissions of the monitor phosphors were measured by the same spectroradiometer to convert photopic troland (Td) to scotopic Td. A chin and head rest was used to stabilize the head position. Pupil diameter was monitored by an Arrington Research ViewPoint EyeTracker 90 fps USB system and software. The sampling rate of this infrared-video-based eye-tracking device was 90 Hz. Participants viewed the monitor with their right eyes from a distance of 57 cm in a dark room, while their left eyes were occluded by an eye patch.

2.3. Visual stimulus

Stimuli similar to those used in Yoshimoto et al. (2017) were tested to compare with our previous findings. The luminance in a 17º uniform field was changed according to the waveform consisting of a 1 Hz fundamental frequency and odd harmonics up to 59 Hz, close to the temporal cut-off frequency under photopic light levels (Kelly, 1961). The flickering field was filtered in the temporal frequency domain and then displayed on a gray background with the same chromaticity (CIE 1931; $x = 0.32$ and $y = 0.34$) and mean luminance. Fig. 1 shows a schematic drawing of waveforms and the amplitude spectra of the stimuli. The phase of each harmonic component was fixed at 0 (square wave phase spectrum) or randomized from 0 to 2π (random wave phase spectrum). The slope of the amplitude spectrum on a log-log scale was set to –1.4, –1.2, –1, –0.8, or –0.6. The waveform with the phase fixed at 0 and with an amplitude slope of –1 approximated a square wave change in time. A steeper slope (< –1) decreased the relative amplitude of higher temporal frequencies resulting in blurred transitions, whereas a shallower slope (> –1) increased the higher frequencies resulting in sharpened transitions. The contrast of each stimulus was rescaled after filtering to maintain a constant root mean square (RMS) contrast of 0.2, 0.1, 0.05, or 0.02.

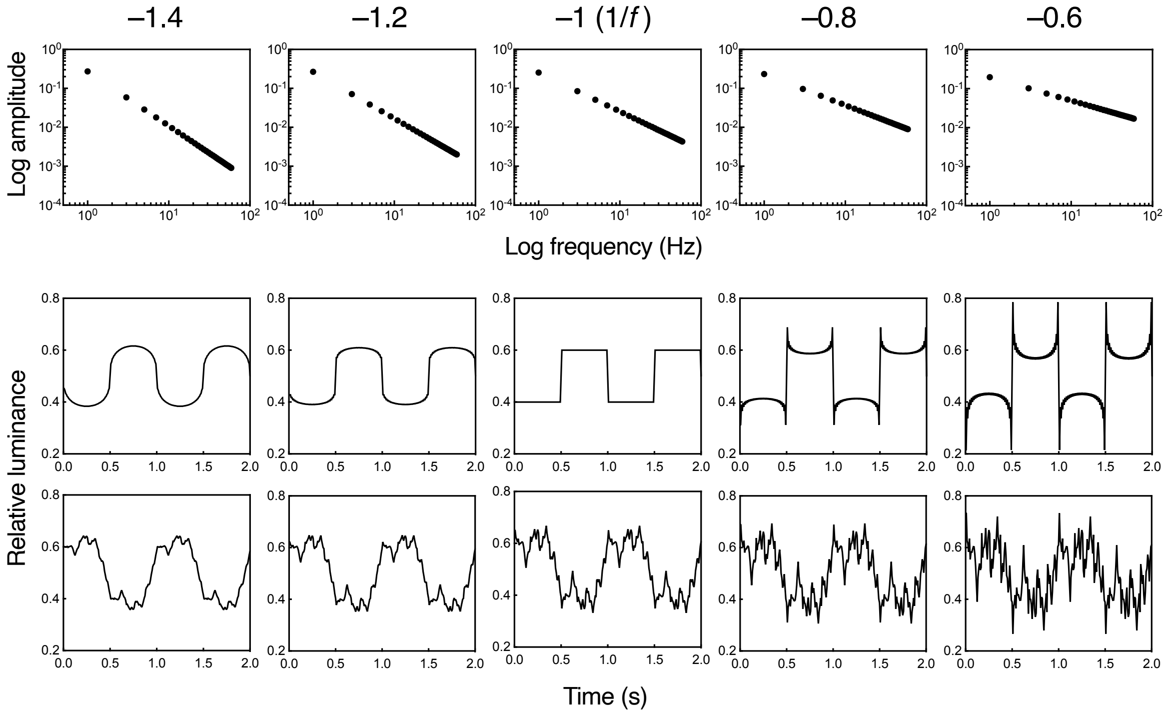

Fig. 1. Stimulus amplitude spectra (1st row). The slope of the amplitude spectrum ranged from –1.4 (left) to –0.6 (right) in 0.2 steps. The amplitude spectrum is plotted as a function of temporal frequency on log-log axes. Schematic drawing of the filtered waveform with square wave (2nd row) or random phase spectra (3rd row). The luminance level of the waveform (relative to a nominal mean level of 0.5) is plotted as a function of time. Movies illustrating the flicker for the different conditions are available in the online supplemental materials.

2.4. Procedure

For each of the following measurements, participants were dark-adapted for 30 min prior to the task. Each measurement began from the darkest adapting levels.

2.4.1. Pupil measurement

Participants' pupil diameters were monitored under the six luminance levels to compute the retinal illuminance. A blank field with a uniform space-averaged luminance was displayed for 5 s while measuring the pupil diameter. The participants were asked to fixate the center of the screen without blinking.

2.4.2. Discomfort measurement

Visual discomfort from the flickering stimuli were quantified by a rating scale similar to that used in previous studies (e.g., Fernandez & Wilkins, 2008; Juricevic et al., 2010, Yoshimoto et al., 2019). This scaling procedure has been commonly used to assess discomfort (Wilkins, 1995). Each stimulus was displayed for 2 s, followed by a gray screen with a 7-point scale (1 = none at all, 7 = a lot). The participants were asked to rate the discomfort of the stimulus by pressing the appropriate number key on the computer keyboard soon after the offset of the stimulus, typically within 1 s. No reference to the scale was made so the participants rated their subjective discomfort without guidance. After the key press, a 1-s uniform field with a space-averaged luminance similar to that of the trial was inserted as an intertrial interval. Each session was composed of 10 trials: two trials for each of the five test stimuli with different amplitude slopes, which were presented in random order. Each participant completed a session for each of the two phase spectra (square wave and random) both at each of the six luminance (46.8, 4.2, 0.35, 0.043, 0.0039, and 0.0006 cd/m^2) at the fixed RMS contrast of stimulus (0.2) and at each of the three RMS contrast (0.1, 0.05, and 0.02) at the fixed luminance (46.8 cd/m^2): 18 sessions in total. For the random waveforms, the phase of the harmonics was randomized on each session.

2.4.3. Contrast threshold measurement

To estimate the visibility (or effective contrast) of the stimulus at each light level and contrast, the thresholds for detecting the stimulus were measured using a two-alternative forced-choice task. The stimulus was displayed for 2 s, which was the same duration as in the discomfort measurement described above, in one of two successive intervals marked by one or two beeps. The participants identified the interval (1st or 2nd) containing the stimulus by pressing the appropriate number key on the computer keyboard. Feedback for correct and incorrect responses were given by high- and low-frequency tones, respectively. The RMS contrast of the stimulus was varied according to the Quest procedure (Watson & Pelli, 1983), which places the most likely contrast on each trial estimated from previous trials and converges at a 75% correct level. In each session, the Quest sequential estimation was terminated after 40 trials. Each participant completed a session for each of the two phase spectra for each of the five amplitude spectra at each of the six luminances: 36 sessions in total. The measurement started from the darkest light levels. For the random waves, the phase of the harmonics was randomized on each session.

2.4.4. Naturalness evaluation

Since natural images generally have a $1/f$ structure in both the spatial and temporal domain, it is expected that perceived naturalness of the visual stimuli could be related to discomfort ratings. In our previous study, we found a close relationship between the discomfort rating and the appearance of naturalness for various types of diffuse flicker under photopic light levels (Yoshimoto et al., 2017). Here, we examined whether the link between naturalness and discomfort is robust for flicker with different contrasts and under different mean light levels.

The procedure was the same as in the discomfort rating, and was again based on a 7-point scale. The participants were asked to rate the perceived naturalness of the stimulus by pressing the appropriate number key on the computer keyboard soon after the offset of the stimulus, typically within 1 s.

3. Results and Discussion

3.1. Pupil measurement

The mean pupil diameters during the 5-s recording were used to calculate the retinal illuminance. The mean retinal illuminance for the six luminance levels ranged from –1.8 to 3.2 log photopic Td. The conversion from photopic Td to scotopic Td was computed for the spectral power distribution of the monitor over a range of 380–780 nm. For the calculation, the CIE photopic V(λ) modified by (Judd, 1951) and (Vos, 1978) and the CIE (1951) scotopic V(λ) were used (Wyszecki & Stiles, 2000). The conversion factor for our monitor was 2.17. According to Hood and Finkelstein (1986) and Stockman and Sharpe (2006), the cone threshold is about –1.4 log photopic Td (–1.0 log scotopic Td) while rod saturation is about 1.9 log photopic Td (2.3 log scotopic Td). Based on this estimation, we assumed that the measured photopic retinal illuminance were categorized as one photopic (2.9 photopic Td or 3.2 scotopic Td), four mesopic (1.9, 1.0, 0.23, and –0.77 log photopic Td or 2.3, 1.4, 0.57, –0.44 log scotopic Td), and one scotopic (–1.6 photopic Td or –1.2 scotopic Td) light level. Note that these categorizations were based on rough estimation of retinal illuminance and used as a reference. The amount of cone and rod activation was not directly measured.

3.2. Discomfort measurement

3.2.1. Effect of light level on discomfort

Fig. 2 shows discomfort ratings for different amplitude and phase spectra at each light level while the RMS contrast of stimulus was fixed at 0.2. Figs. 2a and 2b are for square wave and random phase spectra, respectively. The mean ratings across participants are plotted. Each participant rated the discomfort twice for each amplitude and phase spectrum at each light level. All participants reported that they could see the stimuli at all light levels. To confirm whether the ratings were generally consistent within participants, the intraclass correlation coefficient (ICC) was calculated. Most ICC values were above 0.75, indicating good reliability (Portney & Watkins, 2000). Thus for the subsequent analysis the mean of the two ratings by each participant was used.

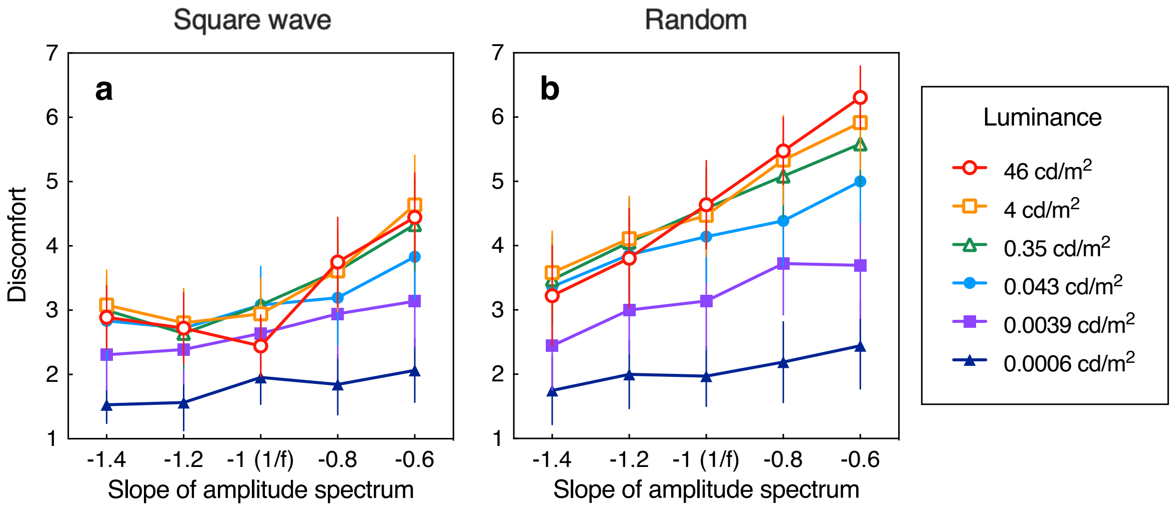

Fig. 2. Mean discomfort ratings across participants for square wave phase spectra (a) and for random phase spectra (b). The discomfort ratings are plotted as a function of the slope of the amplitude spectrum. Each curve represents results for one light level. The error bars represent 95% CI. The RMS contrast of the stimulus was fixed at 0.2.

Square wave phase spectrum: At the photopic light level (46.8 cd/m^2), the plot of the discomfort settings showed an asymmetric V-shape (Fig. 2a), which replicated our previous findings (Yoshimoto et al., 2017). The stimulus that had a 1/*f* amplitude spectrum was rated most comfortable, whereas discomfort increased as the amplitude spectrum deviated in either direction from 1/*f*. Although both steeper (–1.4 and –1.2) and shallower (–0.8 and –0.6) slopes tended to increase the discomfort, the stimuli with shallower slopes appeared more uncomfortable than those with steeper slopes. Decreasing light levels from photopic to middle mesopic levels (46.8–0.043 cd/m^2) removed the minimum in the rating at 1/*f*, without substantially affecting the overall ratings. In contrast, at the lower mesopic and scotopic levels (0.0039 and 0.0006 cd/m^2), the discomfort ratings overall tended to drop, with the largest reductions for the shallower slopes so that the curve gradually became flat.

These results were statistically assessed as follows. A repeated-measures two-way ANOVA was conducted with the factors of amplitude slope and light level in Fig. 2a. The effect size was estimated by generalized eta squared (η^2_G) as recommended for repeated-measures ANOVAs, with 0.02, 0.13, and 0.26 indicating small, medium, and large effects (Bakeman, 2005; Olejnik & Algina, 2003). The main effect of amplitude slope and light level were significant ($F(4, 68) = 26.58, p < 0.0001, \eta^2_G = 0.15$ for the slope; $F(5, 85) = 16.99, p < 0.0001, \eta^2_G = 0.20$ for the light level). The interaction between amplitude slope and light level was also significant ($F(20, 340) = 3.61, p < 0.0001, \eta^2_G = 0.04$). The Tukey's post-hoc test showed significant differences among 1/*f* and shallower slopes (qs ≥ 4.34, ps < .05) at the photopic and mesopic light levels higher than 0.0039 cd/m^2. No significant difference was found among the slopes (qs ≤ 3.51, *ns*) at the scotopic level (0.0006 cd/m^2). The Tukey's test also revealed that the discomfort ratings were significantly different among the photopic (46.8 cd/m^2), low mesopic (0.0039 cd/m^2), and scotopic (0.0006 cd/m^2) levels (qs ≥ 5.96, ps < 0.001). No significant difference was found among the light levels higher than 0.043 cd/m^2 (qs ≤ 3.80, *ns*), except for 1/*f* between 46.8 versus 0.35 cd/m^2 and 46.8 versus 0.043 cd/m^2 (qs ≥ 4.16, ps < .05).

Random phase spectrum: At the photopic light level (46.8 cd/m^2), the discomfort pattern for random phase flicker (Fig. 2b) was different from that for square wave flicker (Fig. 2a), as shown in our previous study (Yoshimoto et al., 2017). At the photopic level, discomfort monotonically increased with shallower amplitude slope. The overall discomfort ratings were again generally similar from photopic to middle mesopic levels (46.8–0.043 cd/m^2), but those for the stimuli with shallower slope (–0.8 and –0.6) were reduced at 0.043 cd/m^2. At light levels lower than 0.043 cd/m^2, the discomfort ratings also again decreased irrespective of the amplitude slope and the curves showed less dependence on the stimulus slope.

Again statistical analyses supported these observations in Fig. 2b. The main effect of amplitude slope and light level were significant ($F(4, 68) = 73.28$, $p < 0.0001$, $\eta^2_G = 0.20$ for the slope; $F(5, 85) = 37.76$, $p < 0.0001$, $\eta^2_G = 0.35$ for the light level). The interaction between amplitude slope and light level was also significant ($F(20, 340) = 6.03$, $p < 0.0001$, $\eta^2_G = 0.05$). The Tukey's post-hoc test showed that the most discomfort ratings were invariant across the higher light levels of 46.8, 4.2, 0.35, and 0.043 cd/m^2 (qs ≤ 3.14, *ns*). At the scotopic level (0.0006 cd/m^2), no significant difference was found among the slopes (qs ≤ 3.20, *ns*), except between –1.4 and –0.6 ($q = 4.71$, $p < 0.01$).

3.2.2. Effect of contrast on discomfort

Fig. 3 shows discomfort ratings for different amplitude and phase spectra at each RMS contrast at the fixed photopic level (46.8 cd/m^2). The data of 0.2 (the highest RMS contrast examined) are replots of the data at 46.8 cd/m^2 in Fig. 2. All participants reported that they could see the stimuli at any RMS contrast.

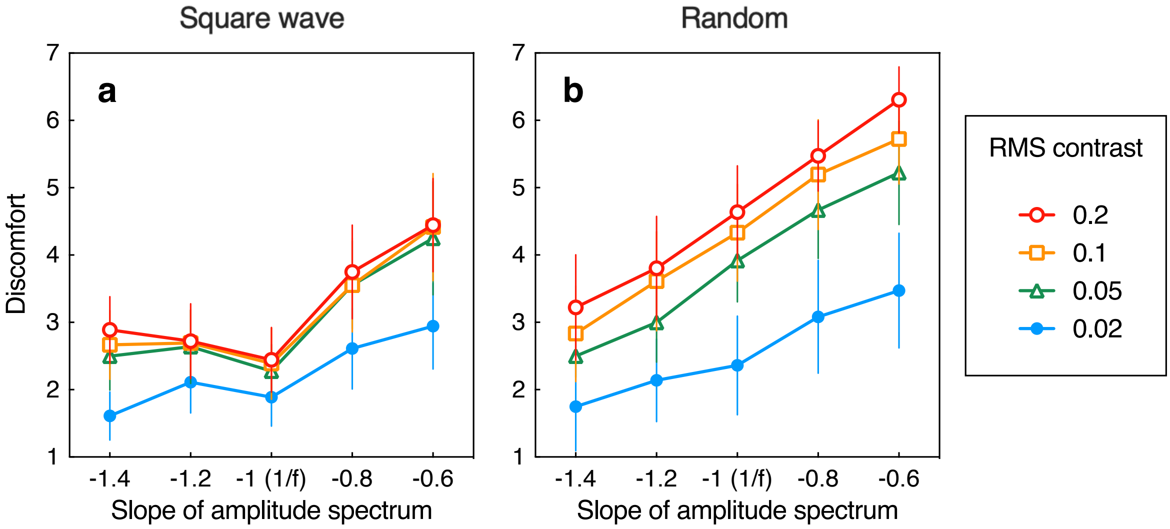

Fig. 3. Mean discomfort ratings across participants for square wave phase spectra (a) and for random phase spectra (b). The discomfort ratings are plotted as a function of the slope of amplitude spectrum. Each curve represents data at a different RMS contrast. The data for the light level of 46.8 cd/m^2 in Fig. 2 are replotted as the data for 0.2 RMS contrast. The error bars represent 95% CI. The light level was fixed at 46.8 cd/m^2.

Square wave phase spectrum: The discomfort ratings were robust to contrast reductions from 0.2 to 0.05 (Fig. 3a). The 1/*f* stimulus again tended to appear most comfortable, and the departure from 1/*f* toward shallower slopes increased the discomfort more than that toward steeper slopes. At the lowest contrast (0.02), the overall discomfort decreased and the V-shape curve was not clearly apparent. In Fig. 3a, the main effect of amplitude slope and RMS contrast were significant ($F(4, 68) = 38.51$, $p < 0.0001$, $\eta^2_G = 0.26$ for the slope; $F(3, 51) = 12.68$, $p < 0.0001$, $\eta^2_G = 0.11$ for the RMS contrast). The interaction between amplitude slope and RMS contrast was also significant ($F(12, 204) = 2.16$, $p < 0.05$, $\eta^2_G = 0.02$). The Tukey's post-hoc test showed that the discomfort ratings were not different among the RMS contrasts of 0.2, 0.1, and 0.05 (qs ≤ 1.58, *ns*), but different between 0.02 and the others (qs ≥ 6.22, ps < 0.0001). At the lowest contrast, no significant difference was found among –1.4, –1.2, and 1/*f* slopes (qs ≤ 3.65, *ns*), whereas the discomfort between –0.8 or –0.6 and the others were significantly different (qs ≥ 5.27, ps < 0.01).

Random phase spectrum: The monotonic increase in discomfort with shallower amplitude slopes was observed irrespective of the RMS contrast (Fig. 3b). However the overall discomfort gradually decreased with the reduction of contrast. The decrease in discomfort for lower contrasts was largest for the shallower slopes such as –0.6. The main effect of amplitude slope and RMS contrast were significant ($F(4, 68) = 96.17$, $p < 0.0001$, $\eta^2_G = 0.33$ for the slope; $F(3, 51) = 26.44$, $p < 0.0001$, $\eta^2_G = 0.26$ for the RMS contrast) in Fig. 3b. The interaction between amplitude slope and RMS contrast was also significant ($F(12, 204) = 2.84$, $p < 0.01$, $\eta^2_G = 0.02$). The Tukey's post-hoc test showed that the discomfort ratings were significantly different among the RMS contrasts (qs ≥ 4.57, ps < 0.05), except between 0.2 versus 0.1 ($q = 1.93$, *ns*) and 0.1 versus 0.05 ($q = 2.64$, *ns*).

Extending our early work (Yoshimoto et al., 2017), we examined the effects of amplitude and phase spectra on visual discomfort along with two further factors that might influence discomfort: the mean light level and the contrast of the flicker. We found in our previous studies (Yoshimoto et al., 2017, 2019) that the square wave stimulus shows a minimum in discomfort for the 1/*f* slope while the random phase spectra instead have a minimum at the steepest slopes. Here we show that this special status for the 1/*f* square wave condition was limited to photopic light levels. At the lower mesopic or scotopic levels, the effect of phase spectrum on the discomfort was diminished, with both phase spectra showing a monotonic change with the slope of the amplitude spectrum (Fig. 2). Thus, discomfort from flicker appeared invariant with phase at scotopic levels yet selective for phase at photopic levels. We also found that stimulus contrast affected the two phases in different ways, with more monotonic effects on the random-phase flicker but weaker contrast dependence for the square-wave pattern.

3.3. Contrast threshold measurement

Fig. 4 shows mean RMS contrast thresholds for detecting the flickering stimuli with different amplitude and phase spectra for the participants. For both square wave and random phase spectra, the contrast threshold steadily increased as the light level decreased. Although the contrast threshold was slightly affected by the amplitude slope, the effect was much smaller than the effect of light level.

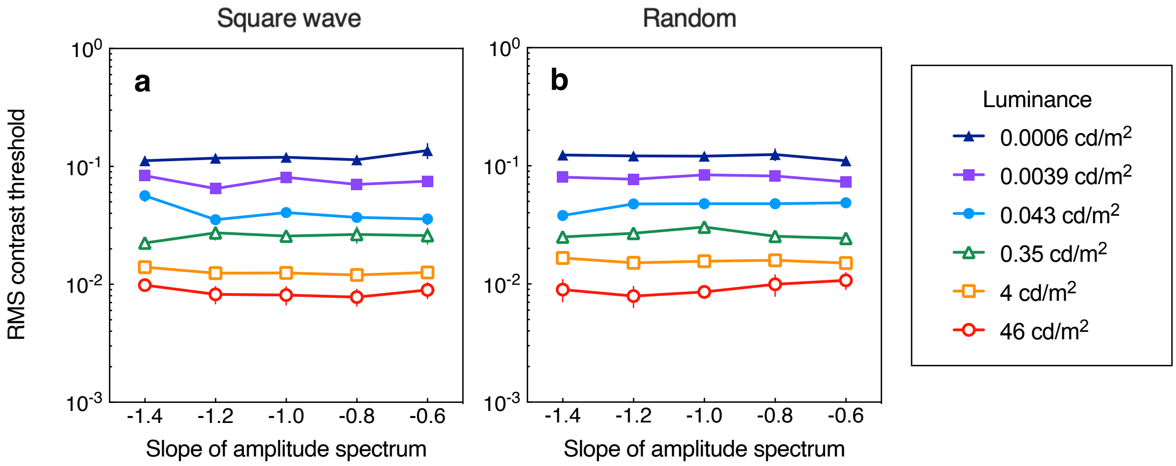

Fig. 4. Mean RMS contrast thresholds across participants for square wave (a) and for random phase spectra (b). The thresholds are plotted as the function of the slope of amplitude spectrum. Each curve represents data for the mean light level in luminance (cd/m^2). The error bars represent 95% CI.

To compare the effects of ambient light level (Fig. 2) and stimulus contrast (Fig. 3) on discomfort based on the visibility (or effective contrast) of the stimulus, we computed the multiple of RMS contrast threshold for the different conditions of light level and contrast by using the results shown in Fig. 4. The multiples were calculated for each participant and then averaged. The discomfort ratings shown in Figs. 2 and 3 are replotted as a function of mean multiple of RMS contrast threshold for the participants in Fig. 5. As shown in this figure, the stimuli were generally rated as most comfortable at the lowest multiple of RMS contrast threshold, and tended to asymptote at higher multiples of threshold. These trends were observed for all conditions, but some differences were also seen between the conditions.

For the square wave phase spectra (Figs. 5a–5e), the discomfort ratings for the 1/*f* amplitude stimulus (Fig. 5c) tended to differ from the results for other slopes (Figs. 5a, 5b, 5d, and 5e). In Fig. 5c, the difference in discomfort between the light level condition (red solid line) and the contrast condition (blue dashed line) was prominent over the range from 5 to 15 times threshold, especially at 5 or 8 times the RMS contrast threshold (indicated by red arrows in Fig. 5c), which corresponded to the average luminance of 0.35 or 0.043 cd/m^2. At these levels the 1/*f* square wave stimulus was rated as more uncomfortable than at the highest multiples of threshold (the rightmost data point in Fig. 5c) (Tukey's test: qs ≥ 4.16, ps $< .05$). This arch-like discomfort curve was not observed in the contrast condition (the blue curve in Fig. 5c). A similar tendency seemed to occur in Fig. 5a, but was not statistically significant (Tukey's test: qs ≤ 3.80, *ns*). At the other slopes for the square wave phase spectrum (Figs. 5b, 5d, and 5e), the discomfort ratings were similar for the light level and contrast conditions.

For the random phase spectrum, the discomfort for the shallower stimulus slopes (–0.8 or –0.6) was very similar between the light level and contrast conditions (Figs. 5i and 5j) whereas the effects diverged for the steeper slopes: discomfort for the light level condition was higher than for the equated contrast condition over the low to middle range of effective contrast (Figs. 5f and 5g). Finally, the 1/*f* random phase spectrum (Fig. 5h) lies in between these two tendencies. The finding that the discomfort ratings did not always match between the mean light level and contrast level conditions when they were normalized for multiples of detection threshold, suggests that stimulus visibility alone cannot predict the overall pattern of discomfort.

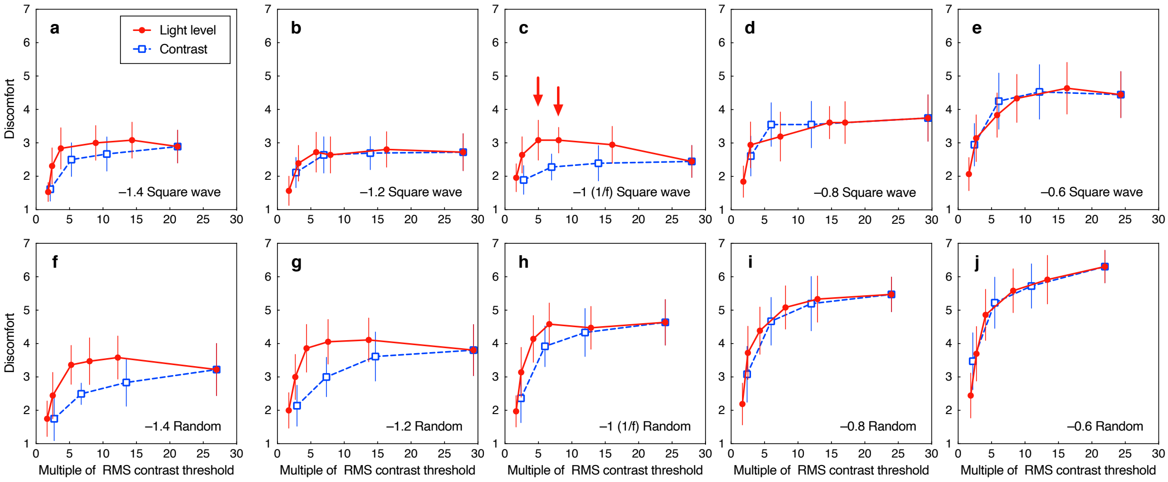

Fig. 5. Replotted data from Figs. 2 and 3. The discomfort rating was plotted as a function of mean multiple of RMS contrast threshold (Fig. 4) for the participants. Each curve represents data at the ambient light level (“Light level”) or RMS contrast of the stimulus (“Contrast”). The error bars represent 95% CI. Panels plot the discomfort ratings for square wave phase spectra with the amplitude slope of (a) –1.4, (b) –1.2, (c) –1 or 1/*f*, (d) –0.8, and (e) –0.6; or for random phase spectra with the corresponding slopes of (f) –1.4, (g) –1.2, (h) –1 or 1/*f*, (i) –0.8, and (j) –0.6. The red arrows in (c) represent the multiples of contrast threshold at which the discomfort was higher than that at the highest multiple of contrast threshold.

3.4 Predictions from a model of the temporal contrast sensitivity function

Many aspects of visual sensitivity can be accounted for by models based on linear spatial or temporal filtering (De Valois & De Valois, 1988). We examined whether such linear filters could predict the discomfort ratings shown in Fig. 2. It is well established that the temporal response of the visual system depends on the mean light level: the shape of the temporal impulse response (TIR) function becomes biphasic to monophasic and the peak response is progressively delayed as the mean light level decreases (Hess, Sharpe, & Nordby, 1990; Ikeda & Shimozono, 1981; Kelly, 1971; Swanson et al., 1987). Generally, the TIR function (or its Fourier-transformed counterpart) is the first stage of computational models for the detection and discrimination of temporally-varying patterns (e.g., Adelson & Bergen, 1985; Watson & Ahumada, 1985). We asked whether the characteristic changes in the TIR function with light level could therefore predict the changes in the discomfort ratings. Specifically, we asked whether stronger responses based on the TIR function predict greater discomfort.

To assess this, we implemented the temporal filtering by convolving the TIR functions described in Fig. 10 of Kelly (1971) with the flicker stimulus shown in Fig. 1. The length of TIR function and flicker were set to 0.2 s and 2.0 s, respectively. In Kelly (1971), the mean light level varied from 1.57 to 1670 td, which partially overlaps with the condition in this study, which varied from 0.026 td (0.0006 cd/m^2) to 819 td (46 cd/m^2). Thus, we set the parameters of the TIR function such that the strength of the negative component or the relative responses between the different light levels was the same as that of Kelly (1971). Fig. 6 shows the time-averaged responses after the temporal filtering of the input flicker. The schematic description of the TIR functions used is shown in the inset of Fig 6. At high light levels, the TIR function is biphasic while it becomes monophasic at low light levels. However, no effect of the slope of amplitude spectrum was observed, while the effect of mean light level was conspicuous. Fig. 6 captures the tendency of the contrast threshold for the flicker to vary with light level as shown in Fig. 4, yet fails to describe the pattern of discomfort ratings in Fig. 2, where the effect of amplitude slope was conspicuous while the effect of mean light level was small, especially between the photopic and high mesopic light levels. These results thus indicate that while changes in the linear filtering with light level could predict the detection threshold of flicker, these changes do not predict the effects of light level on discomfort ratings.

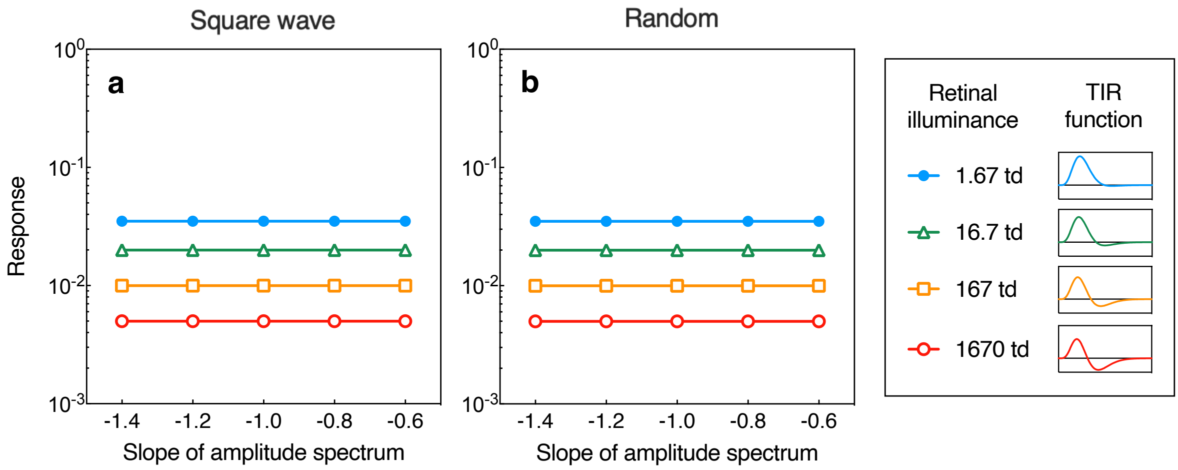

Fig. 6. Time averaged responses after convolving the TIR functions with the input flicker for the square wave phase spectrum (a) and for random phase spectra (b) are plotted as a function of the slope of the amplitude spectrum. Each curve represents predicted responses for a given mean light level in trolands (td). Temporal response functions are from Fig. 10 of Kelly (1971). Schematic depictions of the shape of the TIR function at the corresponding mean light level is shown in the right panel.

3.5 Perceived naturalness of the flicker

In our previous study (Yoshimoto et al., 2017), we showed that the discomfort ratings were consistent with ratings of how natural the stimuli appeared under photopic vision. Fig. 7 shows the perceived naturalness (or unnaturalness) of the flicker for various contrasts at different mean luminance levels. In Fig. 7a (square wave phase transition), the flicker with $1/f$ amplitude spectrum was rated as most natural (i.e., lowest rating value) while this judgment was weaker for both steeper or shallower slopes. As the mean luminance decreased, the slope of the amplitude spectrum that induced the strongest impression of naturalness became steeper. The main effect of amplitude slope and light level were significant ($F(4, 60) = 26.10$, $p < 0.0001$, $\eta^2_G = 0.13$ for the slope; $F(5, 75) = 7.782$, $p < 0.0001$, $\eta^2_G = 0.10$ for the light level). The interaction between amplitude slope and light level was also significant ($F(20, 300) = 2.14$, $p < 0.01$, $\eta^2_G = 0.03$). For random phase spectra, the perceived unnaturalness increased as the slope of amplitude spectrum became shallower, irrespective of the mean luminance level (Fig. 7b). The main effect of amplitude slope and light level were significant ($F(4, 60) = 125.1$, $p < 0.0001$, $\eta^2_G = 0.35$ for the slope; $F(5, 75) = 23.63$, $p < 0.0001$, $\eta^2_G = 0.26$ for the light level). The interaction between amplitude slope and light level was also significant ($F(20, 300) = 7.409$, $p < 0.0001$, $\eta^2_G = 0.08$).

When we instead varied contrast, the unnaturalness impression for the square wave phase spectrum again tended to be lowest for the $1/f$ amplitude spectrum irrespective of the contrast. The main effect of amplitude slope and RMS contrast were significant ($F(4, 60) = 23.53$, $p < 0.0001$, $\eta^2_G = 0.20$ for the slope; $F(3, 45) = 3.117$, $p < 0.05$, $\eta^2_G = 0.07$ for the RMS contrast). The interaction between amplitude slope and RMS contrast was also significant ($F(12, 180) = 2.575$, $p < 0.01$, $\eta^2_G = 0.02$). In comparison, unnaturalness again increased as the slope of the amplitude spectrum became shallower for the random phase transitions (Fig. 7d). The main effect of amplitude slope and RMS contrast were significant ($F(4, 60) = 131.4$, $p < 0.0001$, $\eta^2_G = 0.40$ for the slope; $F(3, 45) = 5.944$, $p < 0.01$, $\eta^2_G = 0.07$ for the RMS contrast). The interaction between amplitude slope and RMS contrast was also significant ($F(12, 180) = 2.322$, $p < 0.01$, $\eta^2_G = 0.02$). Note that this pattern for naturalness ratings (Fig. 7) is very similar to the pattern we observed for the discomfort ratings (Figs. 2 and 3), even though a different set of participants completed the two tasks. The close similarities between the discomfort and naturalness ratings thus suggests that discomfort for the flicker is closely related to how unnatural the flicker appears, irrespective of the mean light level and the contrast.

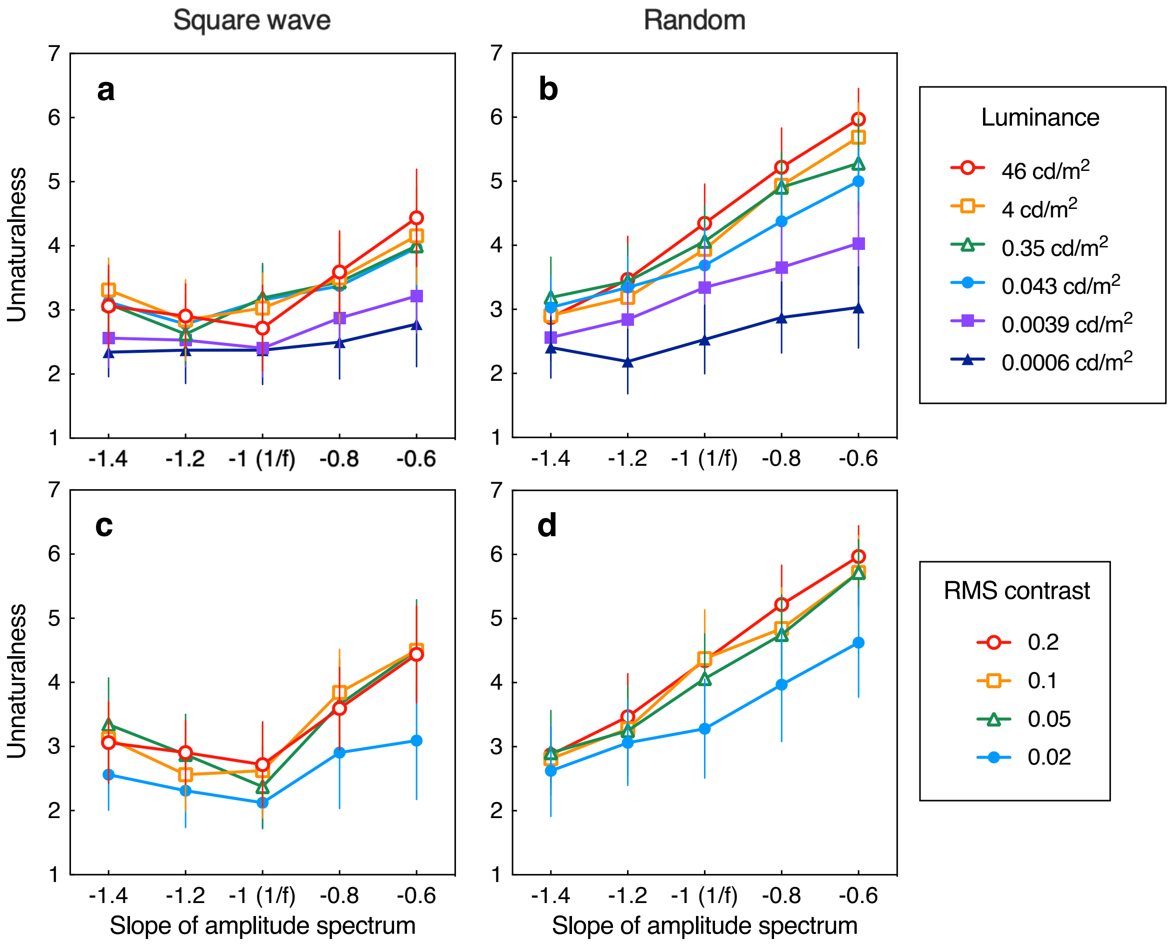

Fig. 7. Mean unnaturalness ratings across participants for square wave phase spectra (a and c) and for random phase spectrum (b and d). Note lower ratings correspond to stimuli perceived as more natural (analogous to lower ratings corresponding to more comfortable). In a and b, each curve represents results for different slopes at fixed light level. The RMS contrast of stimulus was fixed at 0.2. In c and d, each curve reflects settings for different slopes at a fixed RMS contrast. The mean luminance level was fixed at 46.8 cd/m^2. The error bars represent 95% CI.

4. General Discussion

Visual discomfort is an important visual attribute that observers can reliably judge and that varies in systematic ways with the physical properties of the stimulus (Fernandez & Wilkins, 2008; Juricevic et al., 2010; Yoshimoto et al., 2017). Here we examined how ratings of discomfort for temporally varying patterns depend on light level and contrast, stimulus properties that strongly impact the strength and form of the visual response. Changes in both light level and contrast affected the discomfort from flickering patterns in ways that depended on both the amplitude spectrum and phase spectrum of the flicker. However, these effects could not be accounted for by the overall visibility of the pattern or by how the linear temporal response function of the visual system changes with light level. This temporal filtering could predict the detection thresholds for the different patterns across light level, but failed to predict the discomfort ratings (Figs. 4 and 6). Alternatively judgments of how natural the different of types of flicker appeared did correspond closely to how comfortable they were perceived to be (Fig. 7). These results suggest that perceived discomfort from flicker depends on a process specifically sensitive to how the temporal structure of the stimulus deviates from (perceived) temporal statistics of natural visual stimuli.

Regardless of the underlying mechanisms, our results show that the flicker patterns that appear uncomfortable shift at low mesopic and scotopic light levels. Peterson, Ohzawa, and Freeman, (2001) showed that the perceived temporal frequency of flickering patterns was higher than the actual frequency under low luminance conditions, although the response of presumed detectors tuned to high temporal frequencies would be reduced due to the known shift in the frequency domain from band-pass to low-pass temporal characteristics. They argued that the tuning of a subset of cortical cells, which leads to a perception of high temporal frequency, would shift from high to low frequencies with the decrease in luminance level, resulting in the perceived overestimation of frequency (a so-called labelled detector hypothesis). This shift is consistent with the observation that the amplitude slope of the stimulus that was rated as most comfortable shifted to steeper slopes as the light level decreased (Fig. 2a).

In Fig. 5, the discrepancy between the light-level condition and the contrast condition is apparent only in Figs. 5c, 5f and 5g. As found in this study, the discomfort decrement for the flicker with the $1/f$ amplitude spectrum is relatively more invariant to the luminance contrast of the stimulus but dependent on the light level (Figs. 2a and 3a). This characteristic is reflected in Fig. 5c, in which the two functions for light level and contrast do not overlap. For the data of Figs. 5f and 5g, we speculate that the faster growth of the discomfort ratings under the light-level condition than under the luminance-contrast condition might be explained by the labelled-detector hypothesis described above. When the slope of amplitude spectrum is steeper as in Figs. 5f or 5g, lower temporal frequency components of the flicker are overestimated to induce stronger discomfort ratings only in the low light level condition. This kind of overestimation does not occur at low-luminance contrast, thus the two functions in Figs. 5f or 5g do not overlap. The overestimation under low-light levels seems not to affect the discomfort ratings when the phase spectrum was fixed (Figs. 5a or 5b), since the discomfort rating is generally stronger in the random phase condition than in the fixed (square wave) phase condition when the slope of the amplitude spectrum was shallower (thus the higher temporal frequency components are stronger).

Our results also further demonstrate the discomfort from flicker is not simply related to the overall contrast or amplitude spectrum of the stimulus but also depends on the specific “profile” of the stimulus. Square edges in space or time might appear more comfortable because they are more natural stimulus transitions, and blurred or over-sharpened edges might elicit greater discomfort because they deviate from this expected structure. This factor may be relatively less influenced by overall contrast since the change in contrast does not alter the profile, and is consistent with the higher degree of contrast invariance we found for the square waves (Fig. 3a). Alternatively, the random phase would not be subject to this influence as shown in Fig. 3b because the profile is already unnatural or unpredictable. Thus by this conjecture, the square wave and random modulations may give rise to and be dominated by distinct sources of discomfort (degree of unnaturalness and level of stimulation, respectively) which in turn might be differentially modulated by varying the luminance level or contrast of the stimuli.

Natural images are assumed to be efficiently coded by the visual system (Atick, 1990; Atick & Redlich, 1992; Barlow, 1981; Field, 1987; Lennie, 2003; Olshausen & Field, 2004; Párraga, Troscianko, & Tolhurst, 2000; Srinivasan, Laughlin, & Dubs, 1982). Fernandez and Wilkins (2008) and Juricevic et al. (2010) concluded that images having a structure different from $1/f$ would cause less efficient neural processing and therefore greater metabolic demand, which might produce discomfort. This assumption is supported not only by computational modeling studies showing that uncomfortable images produce non-sparse responses in primary visual cortex or V1 (Hibbard & O’Hare, 2015; Penacchio, Otazu, Wilkins, & Harris, 2015), but also by a near-infrared spectroscopy (NIRS) study showing that the images with unnatural statistical properties, which are often uncomfortable to look at, elicit a larger haemodynamic response than for images with more natural properties, which are often comfortable to look at (Le et al., 2017). However, some neuroimaging studies have shown that images with 1/*f* spectra can instead cause stronger cortical responses, presumably due to a more uniform response distribution over different spatial scales (Z. J. Isherwood, Schira, & Spehar, 2017; Olman, Ugurbil, Schrater, & Kersten, 2004).

The different sources described above (degree of unnaturalness and level of stimulation, respectively) might reconcile the discomfort effects with the findings that 1/*f* spectra produce the strongest BOLD responses (Olman et al., 2004; Isherwood et al., 2017, 2018) thus suggesting greater stimulation. By this account, the “unnatural” source of discomfort would not be captured by the BOLD amplitude because it is distinct from the level of stimulation.

A diverse set of factors may therefore underlie different sources of discomfort. Future studies might try to better disentangle these potential sources by exploring whether more nuanced responses can be developed that can potentially distinguish the different “ways” that a stimulus might be visually uncomfortable.

5. Conclusions

There are large qualitative changes in discomfort from flicker with mean light level and contrast. We show that these changes cannot be accounted for by the temporal contrast response function of early visual processing but are closely related to the perceived naturalness of the stimuli. Discomfort from flicker may therefore reflect involvement of a process that is sensitive to the specific profile of the temporal structure of the stimulus.

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