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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 (~1/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.

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 (Chatrian, 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/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 c/°, 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° × 15° 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 naïve 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.