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Amplitude difference and similar time course of impulse responses in positive- and negative-contrast detection

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ABSTRACT

Temporal impulse response functions (IRFs) were measured to investigate the temporal characteristics of positive- and negative-contrast detection in human vision. The IRFs were estimated using models from sequential double-pulse thresholds measured by the psi method. The results indicated that thresholds for positive contrast detection were significantly higher than those for negative contrast detection. However, positive- and negative-contrast IRFs were similar except for the first peak amplitude, reflecting the difference in sensitivity that originates from the summation operation rather than the linear filtering of the visual system.

1. Introduction

A fundamental issue of visual processing is whether positive- and negative-contrast sensitivities are the same. In the psychophysical literature on temporal sensitivity, conflicting results have been reported under various experimental conditions by different investigators.Boynton, Ikeda and Stiles (1964) reported lower decrement thresholds compared to increment thresholds when using a red increment or decrement upon a green background. Short (1966) reported similar results under a low background luminance condition. Patel and Jones (1968) found that the increment threshold was consistently higher than the decrement threshold. Bowen, Pokorny, and Smith (1989) reported greater sensitivity to decrements than increments using saw-tooth contrast stimulation. However, Herrick (1956) and Rashbass (1970) found little difference between increments and decrements. Watson and Nachmias (1977) found that positive thresholds were equal to negative thresholds using grating targets.

Temporal sensitivities measured with numerous types of stimuli have been explained using a generic "working" model (Watson, 1986), which includes a linear filter followed by probability summation over time. In a later model, Watson and Ahumada (2005) used the more general Minkowski summation. The characteristics of the linear filter were investigated by estimating the impulse response function (IRF) or the temporal transfer function of the filter. The IRF is also referred to as the weighting function, which is a linear weighting of sequential inputs and characterizes a time-invariant linear system completely. Theoretically, the IRF can be used to predict the response to any temporally modulated response.

Thus far, psychophysical IRFs have been obtained by various means. They have been calculated from transfer functions by the Fourier transform under various luminance conditions (Kelly, 1961, 1971) and by reconstructing the temporal phase spectrum (Stork & Falk, 1987). From the temporal summation index of positive and negative flashes, hypothetical IRFs of positive and negative flashes were obtained (Ikeda, 1965). Chromatic IRFs derived from responses to red, green, yellow, or blue flashes were also measured (Uchikawa & Ikeda, 1986; Uchikawa & Yoshizawa, 1993). Burr and Morrone (1993) provided a new model set by which to estimate the IRF and measured chromatic and achromatic IRFs. Later, they measured IRFs during saccades (Burr & Morrone, 1996). Shinomori and Werner (2003) investigated age-related changes in IRFs using luminance modulation and for isolated S-cone pathways (Shinomori & Werner, 2006, 2008, 2012). Finally, the reaction time could be estimated using a model based on the IRF (Cao, Zele, & Pokorny, 2007).

In the present study, we tried to investigate the positive- and negative-contrast sensitivity using the double-pulse method with various spatial structure stimuli. First, the detection thresholds of double pulses were compared between positive- and negative-contrast stimuli. Second, the IRFs estimated from sequential double-pulse detection thresholds were also compared in order to investigate the temporal characteristics of positive- and negative-contrast detection. The results indicated that positive contrast detection thresholds were significantly higher than negative contrast detection thresholds. However, this difference was not found in all con-

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ditions and observers in the present study. The present results also indicated that, in terms of temporal characteristics, the IRFs of positive contrast were similar to the IRFs of negative contrast.

2. Methods

2.1. Stimuli

The stimuli in the present study had a circular shape with a 2-D Gaussian envelope, as defined in the following equation:

$$L(x,y) = L_0\left(1 + m\frac{1+\cos\left(2\pi f\sqrt{x^2+y^2}\right)}{2}G(x,y)\right) \quad (1)$$

where L_0 is the background luminance, and m is the amplitude of the cosine function. Here, m was adjusted between 0 and 1 for positive-contrast stimuli, which included only positive-contrast components, and between −1 and 0 for negative-contrast stimuli, which included only negative-contrast components. A higher absolute value of m indicates a higher stimulus contrast. Moreover, m is controlled by the psi (ψ) method in various trials. In addition, f is the spatial structure factor of the stimulus. Since the Fourier spectrum of the stimuli is dominated by low-spatial-frequency components, we use the term 'spatial structure' instead of 'spatial frequency' here. Finally, $G(x,y)$ is a 2-D normal distribution (Gaussian distribution) function with a ±0.3° SD in visual angle. Positive- and negative-stimulus images and their corresponding luminance profiles are illustrated in Fig. 1.

Double-pulse stimuli were presented in one of four quadrants defined by a central fixation cross on a 10 cd/m^2 background, which had the same chromaticity as the stimulus (equal-energy-white). Both the width and height of the center cross were 2° in visual angle. The four stimuli were alternately located 0.71° to one side or the other and 0.71° above or below the center of the fixation cross. The background was approximately 6° in width and 4° in height.

In double-pulse method, the contrast threshold is commonly measured as the detection threshold. The contrast itself at a certain point, (x,y), can be defined by the intensity of a single pulse, $I_T(x,y)$, against the background intensity, I_B, for the duration of the pulse. In order to compare positive and negative contrast equitably, the contrast, $C(x,y)$, was defined as shown in Eqs. (2) and (3). The negative contrast was transformed to its mirror value along the background intensity axis.

$$C(x,y) = \frac{I_T(x,y)}{I_B}, \quad I_T(x,y) \geqslant I_B \quad (2)$$

$$C(x,y) = \frac{2I_B - I_T(x,y)}{I_B}, \quad I_T(x,y) < I_B \quad (3)$$

In order to determine the contrast of the stimuli in different spatial structures, we used the contrast energy concept and defined the contrast energy, C_E, as shown in Eq. (4), which was modified from the definition given by Watson, Barlow, and Robson (1983):

$$C_E = \frac{1}{mn}\sum_{x=1}^{m}\sum_{y=1}^{n}C^2(x,y) \quad (4)$$

where $C(x,y)$ is the contrast of the stimulus at (x,y) in each screen pixel. Thus, m and n indicate the size of the stimulus in the pixel. The thresholds for the double-pulse method are defined as the log contrast energy, $\log(C_E)$.

In the stimulus design, pulses were presented within an angular range of 4°, and the highest luminance peaks were presented

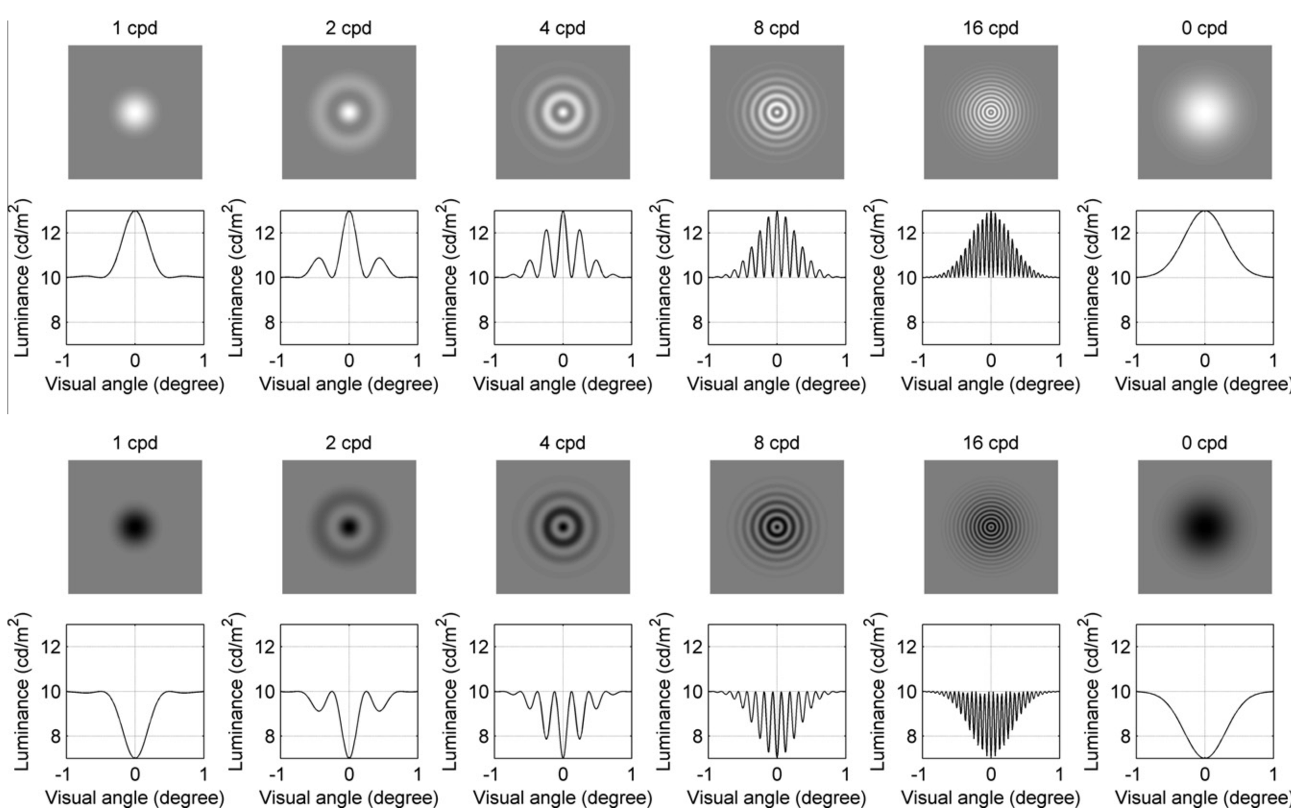

Fig. 1. Stimuli and corresponding luminance profiles with the same maximum luminance amplitude. The first two rows are for positive contrast stimuli, and the last two rows are for negative contrast stimuli. The first and third rows are images of stimuli having different spatial structures, 1, 2, 4, 8, 16, and 0 cpd. The second and forth rows are luminance profiles of stimuli.