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Brightness masking is modulated by disparity structure

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ABSTRACT

The luminance contrast at the borders of a surface strongly influences surface's apparent brightness, as demonstrated by a number of classic visual illusions. Such phenomena are compatible with a propagation mechanism believed to spread contrast information from borders to the interior. This process is disrupted by masking, where the perceived brightness of a target is reduced by the brief presentation of a mask (Paradiso & Nakayama, 1991), but the exact visual stage that this happens remains unclear. In the present study, we examined whether brightness masking occurs at a monocular-, or a binocular-level of the visual hierarchy. We used backward masking, whereby a briefly presented target stimulus is disrupted by a mask coming soon afterwards, to show that brightness masking is affected by binocular stages of the visual processing. We manipulated the 3-D configurations (slant direction) of the target and mask and measured the differential disruption that masking causes on brightness estimation. We found that the masking effect was weaker when stimuli had a different slant. We suggest that brightness masking is partly mediated by mid-level neuronal mechanisms, at a stage where binocular disparity edge structure has been extracted.

1. Introduction

The perceived brightness of a surface differs substantially from its photometric luminance. A number of classic visual illusions demonstrate the important role that contrast edges play in the visual appearance of an enclosed surface. For instance, when viewing the Craik–O'Brien–Cornsweet illusion, observers interpret isoluminant areas as having different brightness due to the luminance intensity ramps at their edges. The spatial influence of such contrast edge effects can be extensive (for example, Adelson, 2000; Komatsu, 2008).

Such phenomena can be understood in terms of the operation of spatial filtering processes that act at very early stages (pre-cortical) of visual processing (Blakeslee & McCourt, 1999; McArthur & Moulden, 1999; Otazu, Vanrell, & Parraga, 2008; Watt & Morgan, 1985). Alternatively, higher-level explanations have been offered on the basis that the brain employs propagation mechanisms ("filling-in"), whereby attributes encoded at one portion of the scene (e.g., contrast edges) influence the perceptual appearance of stimulus attributes that the visual system appears less ready to encode (e.g., regions of homogenous intensity) or unable to sense (e.g., due to the retinal blind spot) (Anstis, 2010; Komatsu, 2006; Pessoa, Thompson, & Noe, 1998). Electrophysiological recordings from the visual cortex provide some support for the notion that neural activity spreads across the cortex during presentation of displays that involve filling-in effects (De Weerd et al., 1995; Lamme, Rodriguez-Rodriguez, & Spekreijse, 1999). This lateral spreading of activity may provide part of explanation for the absence of 'missing' information in our perceptual interpretation of the world, and is compatible with psychophysical evidence for the lateral spread of contrast information across the cortical surface (Davey, Maddess, & Srinivasan, 1998).

One means of studying the mechanisms of brightness perception is to interfere with the putative filling-in mechanisms that may support it. Paradiso and Nakayama (1991) developed such an approach using metacontrast masking, reasoning that if brightness estimation involves the spread of activity from the border of a surface towards its interior, then it should be possible to interrupt it. Specifically, they hypothesized that if contrast information is propagated from contrast edges, the subsequent presentation of new border signals should interfere with the filling-in process before it was completed. They found that the brightness at the centre of a uniform target was considerably reduced when followed (50–100 ms) by a briefly presented circular mask (concentric with

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the target). Moreover, they observed a trade-off between the distance between the edges of the target and mask and the time at which the mask had a suppressive effect on brightness, which they suggested was compatible with a filling-in process where spreading of activity occurred at around 130 deg/s. They further observed that masking was greater under dichoptic presentation (target and mask presented to different eyes) than under monoptic presentation: in the former case, dramatic brightness suppression occurred even with simultaneous presentation of target and mask. This indicates that binocular processes are involved in the estimation of brightness, indicating contributions at the cortical level, although effects of rivalry or binocular summation could not be separated.

Information about three-dimensional scene structure has previously been suggested to be important for brightness estimation. For instance, computational models of early visual processing and brightness estimation (Grossberg & Mingolla, 1985; Grossberg & Todorovic, 1988) posit a role for disparity signals in constraining filling-in mechanisms for brightness (Kelly & Grossberg, 2000). Moreover, high-level theories of brightness (Adelson, 1993) and lightness (e.g., Anderson & Winawer, 2005; Gilchrist, 1977; Knill & Kersten, 1991) incorporate information about the three-dimensional scene structure that is available from the image.

Here we sought to test the contribution of disparity-defined three-dimensional scene information in guiding the impression of brightness by employing a modified version of the paradigm developed by Paradiso and Nakayama. In particular, we asked whether the brightness reduction induced by a mask was affected by the depth configuration of the target and mask. We reasoned that if brightness estimation takes place at a low level of processing (i.e. before depth estimation has occurred) we would find no change in the effect of a briefly presented mask when the mask and target had the same or opposite disparity-defined slants. However, if brightness estimation involves binocular disparity edge information, we anticipated that masking would be greatest when the target and mask where spatially coincident. In our first experiment we considered the effects of opposite slants for the target and mask. In experiment two, we then examined the sensitivity of the masking effect to gradations of slant differences between the target and mask.

2. Methods

2.1. Participants and apparatus

Eleven participants (including authors H.B. and V.P.) took part in Experiment 1 (mean age = 27.7, *SD* = 4.58; 3 females) and nine in Experiment 2 (mean age = 27.4, *SD* = 4.67; 1 female). All participants except the authors were naïve to the purpose of the study and were recruited from staff and students at the University of Birmingham and the University of Cambridge. All had normal or corrected to normal vision, and provided written informed consent. They were screened to ensure they could reliably discriminate depth positions defined by at least 1 arcmin of horizontal disparity. The protocols for the experiment were approved by the University of Birmingham's STEM ethics committee. The work was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Stimuli were viewed through a mirror stereoscope, where the two eyes viewed separate gamma corrected CRT (ViewSonic FB2100X) monitors from a distance of 50 cm. Screen resolution was 1600 × 1200 pixels at 100 Hz. Luminance calibration was achieved by linearizing grey-level values using a Minolta LS110 photometer. Presentation monitors were recalibrated regularly to ensure that stimulus luminance was constant for different participants and across experiments.

2.2. Stimuli and procedure

The stimuli were circular target disks (diameter = 12°) and a mask which was an unfilled circle (diameter = 5.2°; line width = 0.4°) (Fig. 1). One of the targets (the reference; 'target 1' in Fig. 1c) was a uniform disk (luminance of 101.7 cd/m^2) while the other target (the test; 'target 2' in Fig. 1c) had a centre-surround configuration with a blurred interior boundary (see Fig. 1b). The diameter of the centre portion was 5.2°, and we applied blur to the boundary using a 2-D Gaussian-kernel of FWHM = 0.2°. The luminance of the centre portion of the disk in the test target was controlled by an adaptive staircase and varied from 101.7 to 135 cd/m^2; the surround had a constant luminance of 101.7 cd/m^2.

Prior to taking part in the experiment, participants were dark adapted for 5 min, followed by two minutes of passive viewing on a mid-level grey patch of 67.8 cd/m^2 (this corresponded to the background luminance during stimulus presentation). Brightness judgments were measured using a two interval forced choice paradigm where the inter-stimulus interval (ISI) was 800 ms. During the reference interval, a single disc with a uniform luminance of 101.7 cd/m^2 was presented for 60 ms. During the test interval, a target disc (with variable luminance at its centre) was followed by the mask after a pre-defined time interval (stimulus onset asynchrony – SOA). The order of the reference and test stimulus presentation was randomised. We measured luminance increment thresholds, defined as the just noticeable difference. In particular, participants judged whether the first or the second target had a brighter centre. Thresholds were calculated using the QUEST staircase method (Watson & Pelli, 1983) to obtain the 82% threshold. Luminance was decreased after three successive correct responses, but increased after one incorrect response (i.e., 3-up and 1-down staircase).

2.3. Masking properties

For the test interval presentations, a mask was presented after the target stimulus (metacontrast backward masking; see Breitmeyer & Ogmen, 2000, 2006). The mask was centred on the target, and had the same diameter (5.2°) as the centre portion of the target. The target and the mask remained on screen for 60 ms each, while the exact interval (SOA) between them was tailored to individual participants (see Section 2.4 below).

2.4. Stimulus onset asynchrony (SOA) estimation

Prior to taking part in the main experiments, participants completed a session designed to estimate their SOA threshold. It is known that masking is a function of the SOA (Alpern, 1953), with little masking at either very short or long SOAs, but dramatic reductions in target's visibility in-between. Paradiso and Nakayama (1991) tested the influence of SOA on brightness masking finding maximal effects for an SOA of 50–100 ms. Other studies on backward masking find SOA time-windows for optimal target suppression vary in the range 30 and 150 ms (Breitmeyer & Ogmen, 2006, p. 38; Green et al., 2005; Polat, Sterkin, & Yehezkel, 2007), with differences between individual participants. We therefore chose to tailor the maximal masking effect by identifying optimal values for each participant.

This testing session consisted of three blocks of 50 trials. Stimuli were orientated in the fronto-parallel plane. The participants' task was to indicate which interval had the brighter centre, and we estimated increment thresholds that gave the maximum masking effect using the QUEST method. We found that estimated SOA thresholds for two participants exceeded 250 ms, which is outside the range expected for genuine metacontrast masking. We retested these (naïve) participants in a second session and again found SOA