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More superimposition for contrast-modulated than luminance-modulated stimuli during binocular rivalry

Jan Skerswetat*, Monika A. Formankiewicz, Sarah J. Waugh

Anglia Vision Research, Department of Vision and Hearing Sciences, Anglia Ruskin University, East Road, CB1 1PT Cambridge, UK

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ABSTRACT

Luminance-modulated noise (LM) and contrast-modulated noise (CM) gratings were presented with interocularly correlated, uncorrelated and anti-correlated binary noise to investigate their contributions to mixed percepts, specifically piecemeal and superimposition, during binocular rivalry. Stimuli were sine-wave gratings of 2 c/deg presented within 2 deg circular apertures. The LM stimulus contrast was 0.1 and the CM stimulus modulation depth was 1.0, equating to approximately 5 and 7 times detection threshold, respectively. Twelve 45 s trials, per noise configuration, were carried out. Fifteen participants with normal vision indicated via button presses whether an exclusive, piecemeal or superimposed percept was seen. For all noise conditions LM stimuli generated more exclusive visibility, and lower proportions of superimposition. CM stimuli led to greater proportions and longer periods of superimposition. For both stimulus types, correlated interocular noise generated more superimposition than did anti- or uncorrelated interocular noise. No significant effect of stimulus type (LM vs CM) or noise configuration (correlated, uncorrelated, anti-correlated) on piecemeal perception was found. Exclusive visibility was greater in proportion, and perceptual changes more numerous, during binocular rivalry for CM stimuli when interocular noise was not correlated. This suggests that mutual inhibition, initiated by non-correlated noise CM gratings, occurs between neurons processing luminance noise (first-order component), as well as those processing gratings (second-order component). Therefore, first- and second-order components can contribute to overall binocular rivalry responses. We suggest the addition of a new well to the current energy landscape model for binocular rivalry that takes superimposition into account.

1. Introduction

Binocular rivalry refers to visual competition that arises when different images are presented separately to each eye (e.g. Brascamp, Klink, & Levelt, 2015; Levelt, 1965; von Helmholtz, 1867; Wheatstone, 1838). Visual stimuli such as gratings presented at orthogonal orientations, e.g. a horizontal grating to the left eye and a vertical grating to the right eye, generate perceptual alternations from one exclusively visible grating to the other. However, mixed states of both gratings in one percept can occur in the form of piecemeal rivalry in zones, so that a percept contains portions of each grating (e.g. Blake, O'Shea, & Mueller, 1992). Near contrast detection threshold, orthogonally orientated grating stimuli can appear to overlap, a percept referred to as a 'dichoptic plaid' (Liu, Tyler, & Schor, 1992) or 'superimposition' (e.g. Brascamp, van Ee, Noest, Jacobs, & van den berg, 2006). If rivalling stimuli with very different spatial frequencies are presented, they can begin to superimpose and can be perceived in different depth planes (Yang, Rose, & Blake, 1992).

Piecemeal percepts are suggested to represent rivalry within small spatial zones throughout the visual field. They occur for larger stimuli, but have been described for stimulus sizes as small as 10 arcmin (Blake et al., 1992). Blake et al. (1992) designed a model in which rivalry develops via independent, adjacent, non-overlapping interacting retinal areas. Spatial concatenations of multiple zones in different exclusivity states were thought to result in piecemeal percepts during binocular rivalry. Whereas superimposition is thought to be an indicator of binocular fusion (Brascamp et al., 2006; Liu et al., 1992).

Whether an exclusive or a mixed percept occurs during binocular rivalry can depend on low-level stimulus characteristics (i.e. those initially processed in early stages of the visual cortex) such as size (e.g. Blake et al., 1992; Breese. Burti, 1899; O'Shea, Sims, & Govan, 1997), contrast (e.g. Bossink, Stalmeier, & de Weert, 1993; Brascamp et al., 2015; Levelt, 1965), orientation (e.g. Schor, 1977; Wade, 1974) and spatial frequency (e.g. Kitterle & Thomas, 1980; O'Shea et al., 1997). The level of stimulus complexity also influences the course of binocular rivalry alternation (e.g. Alais & Melcher, 2007; Nguyen, Freeman, &

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* Corresponding author.
E-mail address: jan.skerswetat@anglia.ac.uk (J. Skerswetat).

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Alais, 2003; but see also Kovács, Papathomas, Yang, & Feher, 1996). Gratings or circles are considered to have low complexity, whereas houses or faces are thought to be complex stimuli in this context, as they require more cognitive or semantic computation (see Lumer, Friston, & Rees, 1998 but also Blake & Logothetis, 2002).

All of the studies described above used luminance-based or coloured gratings or objects (so-called first-order spatial stimuli), which are differentiated from their backgrounds by a change of mean luminance or colour. Contrast-modulated noise (CM) stimuli (i.e. a type of second-order stimulus) can be perceived even though they do not show variations of mean luminance across a stimulus but only variations in contrast (e.g. Chubb & Sperling, 1988; Landy & Graham, 2004; Mareschal & Baker, 1999; Schofield & Georgeson, 1999; Zhou & Baker, 1993). Results from a number of psychophysical studies (e.g. Chima, Formankiewicz, & Waugh, 2015; Hairol & Waugh, 2010a; Schofield & Georgeson, 1999), an electrophysiological study (Calvert, Manahilov, Simpson, & Parker, 2005), a neuro-imaging study (Larsson, Landy, & Heeger, 2006), and neurophysiological studies in cats (Mareschal & Baker, 1998; Tanaka & Ohzawa, 2006) and macaques (An et al., 2014; Li et al., 2014) have led to suggestions that additional computation is necessary in order for second-order stimuli to be perceived, compared to first-order stimuli (e.g. Baker, 1999; Landy & Graham, 2004; Schofield & Georgeson, 1999). Results from studies on amblyopia and interocular suppression suggest that this extra computation occurs in an area that involves binocular neurons (Chima, Formankiewicz, & Waugh, 2016; Wong, Levi, & McGraw, 2001, 2005). Dynamics of binocular rivalry are affected by a number of stimulus attributes (as outlined above), but in the present study, we are specifically concerned with differences that arise as the result of using LM and CM stimuli whilst keeping all other stimulus properties the same. Any differences in the characteristics of rivalry should therefore reflect the different processing sites for the two stimulus types.

In a recent study, we investigated binocular rivalry characteristics for orthogonally orientated gratings created using sinusoidal modulations of luminance (L), luminance modulated noise (LM) and contrast modulated noise (CM) (Skerswetat, Formankiewicz, & Waugh, 2016). We demonstrated that even under comparable visibility levels (multiples above detection threshold), a greater proportion of "mixed" percepts was evident for rivalling CM, than LM stimuli. This result in normal vision provides further support for the suggestion that more binocular areas are engaged in the processing of CM, than LM stimuli. However, as noted above, "mixed" percepts likely consist of both piecemeal and superimposition.

The first aim of the current study is to quantify the proportions of piecemeal and superimposition that occur during binocular rivalry for LM and CM stimuli. If CM stimuli are first processed by units involved in binocular fusion (e.g. Chima et al., 2015; Hairol & Waugh, 2010b; Wong et al., 2001, 2005), then significantly greater proportions of superimposition would be found for CM, than for LM stimuli. The second aim of the current study is to investigate the effects that different interocular luminance noise correlations have on binocular rivalry characteristics. If rivalry is initiated when luminance information is extracted, both LM and CM rivalry dynamics should change in a similar way only when noise is not fully correlated.

2. Methods

2.1. Participants

Eight male and seven female participants with an average age of 25.7 ± 5.2 years carried out the experiment. Three were experienced in binocular rivalry experiments. All except one participant (author J.S.) were naïve to the purpose of the study. All participants had normal or corrected-to-normal visual acuity of at least 6/6 and normal binocular vision as indicated by random-dot-stereopsis of at least 60 arcsec when measured with the Dutch Organization for Applied Scientific Research (TNO) stereo test (Lameris Ootech, Ede, Netherlands).

2.2. Stimuli

All stimuli were presented in a circular aperture of 2 deg diameter and contained a 2c/deg sinusoidal grating. The left eye's stimulus contained a horizontal grating, and the right eye's, a vertical grating. LM gratings were created by adding dynamic two-dimensional binary noise with an amplitude of 0.2 to a sine-wave with luminance modulation of 0.1. The same noise amplitude was multiplied by the sine-wave to create the CM gratings with a modulation of 1.00. It is important to consider the visibility of stimuli used to generate binocular rivalry since luminance contrast (and therefore visibility) of first-order stimuli influences the course of rivalry (e.g. Brascamp et al., 2015; Levelt, 1965). In a previous study, we measured detection thresholds for CM and LM stimuli of the same size, spatial frequency as used in the current study (Skerswetat et al., 2016). Based on these detection thresholds (averaged across participants), for the modulations used in this experiment, the visibilities for the two types of stimuli are similar, at 7 ± 1 (standard error) times and 5 ± 1 times for CM and LM stimuli, respectively.

The stimulus types can be mathematically described as follows.

Sinusoidal luminance-modulated (LM) grating:

$$l_0(x,y) = l_0[1 + nN(x,y) + l\sin(2\pi x f_x)$$

Two-dimensional binary white noise added to a sinusoidal luminance grating. N is the binary noise at position (x,y) (either black (-1) or white (1)) and n is contrast of 0.2.

Sinusoidal contrast-modulated (CM) grating:

$$l_0(x,y) = l_0[1 + nN(x,y) + nN(x,y)m\sin(2\pi x f_x)$$

Contrast modulation is m. The mathematical term $nN(x,y)m\sin(2\pi x f_x)$ expresses the contrast-modulated grating that results from the multiplying random noise sample by a sinusoid (Calvert et al., 2005; Schofield & Georgeson, 1999).

Stimuli were presented on a grey background with a mean luminance of 48.55 cd/m^2. The stimuli were viewed through a stereoscope. The optical distance from the participant's eyes through the mirrors to the monitor was 100 cm. The pixel size at this distance was 1.3 arcmin. A surrounding annulus with a diameter of 4 deg and a width of 2.6 arcmin (2 pixels) was used as a fusion lock (see Fig. 1).

Three different noise configurations were used. 'Correlated noise' refers to noise checks that correspond interocularly in space, time and luminance. 'Anti-correlated noise' refers to noise checks that correspond interocularly in space and time, but with opposite luminance values. 'Uncorrelated noise' refers to noise checks that randomly correspond interocularly in space and time, thus, there is a 50% chance that a particular check in one eye also corresponds in luminance with the same check in the other eye. At 100 cm, each noise check subtended 2.6 arcmin (or 2 × 2 pixels).

To avoid any first-order artefacts in the second-order stimuli due to pixel clumping of static noise, dynamic noise was used (e.g. Ellemberg, Allen, & Hess, 2004; Georgeson & Schofield, 2016; Hairol & Waugh, 2010a; Schofield & Georgeson, 1999, 2000; Zhou, Liu, Zhou, & Hess, 2014). Ten stimulus pages were created using the equations above, each with a different, random noise pattern. These ten pages were cycled in random order for the duration of the trial to generate dynamic noise. Each page was displayed for two monitor frames with the monitor running at 140 Hz. Consequently, the noise checks across the stimulus changed every 14.28 ms in both stimuli.

2.3. Apparatus and monitor calibration

The stimuli were presented on a Mitsubishi Diamond Pro 2070SB CRT Monitor with a resolution of 1027 × 769 pixels. Dell Precision 3500 hardware and Microsoft Windows XP Professional (Version 2002) software were used to run the experiment and store the data. A customised MatLab program (Version R2010b) in combination with the