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Summation of target and mask metacontrast stimuli

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Abstract. Three experiments are reported; they show the following: (i) Metacontrast occurs at high photopic conditions (250 cd m^{-2}); at this luminance the function peaks at stimulus asynchronies of ~40 ms (compared with 100 ms at lower luminances). (ii) The strength of metacontrast is contrast-independent, down to contrast very near detection threshold. (iii) Detection thresholds for the combined target and mask presentation are lower than those for the mask alone, implying summation between target and mask. Summation is greatest at the same asynchronies which yield maximum metacontrast masking. The experiments are taken as evidence in favour of a fusion explanation for metacontrast. An argument is made which implicates temporally units of the motion detection system as being instrumental in the fusion process.

1 Introduction

'Metacontrast' is the term introduced by Stigler (1910) to describe the reduction in brightness of a flash of light when followed at a suitable interval by an adjacent flash (or flashes). Since then numerous researchers have interested themselves in this curious phenomenon (notably Fry 1934; Pieron 1935; Alpern 1953; Weisstein 1968), whose work has been well summarized in the reviews of Alpern (1952), Weisstein (1975), Lefton (1973), and Breitmeyer and Ganz (1976).

Early explanations of metacontrast were couched in terms of inhibition by the second stimulus of the neural response to the first with some delay occurring for signals of the first stimulus during their passage through the visual pathways (see, for example, Stigler 1913; Fry 1934; Pieron 1935). More recently this idea has been expanded and developed by many workers, perhaps the most explicit model being the Rashevsky two-factor neuron theory of Weisstein (1968).

A problem facing all inhibition theories is how (and indeed why) the neural response of the first stimulus is delayed sufficiently to coincide with that of the second. Weisstein argues that inhibitory neural processes are faster than excitatory ones. Although there does exist some supportive neurophysiological evidence for this, the latencies involved do not seem to be adequate to be consistent with the metacontrast function. For example, the cortical intracellular recordings of Singer et al (1975) reveal that the presynaptic inhibitory potential typically precedes the postsynaptic excitatory potential by about 2 7 ms, while maximum metacontrast is often reported at latencies of about 100 ms (see, for example, Alpern 1953).

Other mechanisms for the delay have been suggested, including the notion of Breitmeyer and Ganz (1976), where purported 'transient' channels inhibit 'sustained' channels.

An alternative class of theories suggests that rather than one stimulus inhibiting the other, the two become perceptually 'fused', so that they are no longer seen as separate identities (see, for example, Fehrer 1966; Schiller and Smith 1966; Stoper and Banffy 1977).

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The experiments reported here examine the two notions of inhibition and fusion, by use of the summation technique (Fiorentini and Mazzantini 1966; Sachs et al 1971). If inhibition is the cause of metacontrast, the two test and mask stimuli should be detected independently at threshold. If, however, they are perceptually fused, then the energy of test and mask should be added, yielding a lower detection threshold on combined presentation.

2 Methods

2.1 *Stimuli*

The stimuli were generated by computer (PDP/11-03) and displayed on the face of a Joyce Electronics oscilloscope (white phosphor). The screen was illuminated to a background luminance of 250 cd m^{-2}, on which the metacontrast stimuli were superimposed. Linearity of the oscilloscope was checked with a Spectra Pritchard spot photometer and found to be accurate within the measuring accuracy of the instrument (0.1%) over the luminous range employed in these experiments. The screen (20 cm x 20 cm) was surrounded by a 1 m^2 screen illuminated to match that of the oscilloscope background (250 cd m^{-2}). Observers viewed the display from a distance of 40 cm, with appropriate optical correction of accommodation. Note that the luminances used in this study are somewhat higher than those generally used in metacontrast experiments.

Stimuli were displayed on the oscilloscope face with a raster display technique at 200 frames s^{-1}, 1000 lines $(frame)^{-1}$. Target and mask stimuli were presented for one frame, lasting 5 ms. The target was a horizontal bar, 1 deg x 28 deg, centered 4 deg above or below a heavy fixation point. The mask comprised two horizontal bars, each 1 deg x 28 deg, separated by 1 deg, and positioned to flank the target. (Note that these are somewhat longer than normally used.) The mask appeared after the target at a variable asynchrony. The luminance of the bars could be varied above or below that of the background, but was typically greater than the background.

2.2 *Rating scales*

The metacontrast function was obtained by rating the apparent strength of the masking at various stimulus asynchronies. After some experimentation, the following procedure was found to yield the most reliable results.

On each trial, the observer was first presented with a 'standard' metacontrast complex, comprising a target and mask of 40 ms offset asynchrony (chosen because it yields maximum metacontrast masking at these luminances). This was followed, after a 500 ms pause, by the 'test' metacontrast complex which the observer rated. The standard was centered 4 deg above the fixation mark and the test 4 deg below. The reason for the standard was to help observers keep a constant criterion. The observers rated the amount of masking (apparent reduction in luminance of the target) for the test stimuli on a scale of 1 to 6: a value of 1 corresponded to no reduction in masking; a value of 6 to a reduction equal to that seen with the previously viewed standard.

Responses were made by pressing one of six touch-identifiable buttons connected to the digital interface of the computer. The computer registered the response and computed means and standard errors for each asynchrony.

Ten ratings were made for each asynchrony, all within a single session in which the presentation order was randomized.

2.3 *Strength of metacontrast*

Brightness-matching measures were obtained by requiring observers to match the apparent luminance of the target bar of a metacontrast complex with that of a standard, presented with its flanking bars with no temporal offset. The metacontrast stimuli and standard were presented alternatively every 500 ms, 4 deg above and below the fixation point respectively. The standard was designed to emulate the spatial, but not the temporal configuration of the metacontrast stimuli. Like the metacontrast complex, it comprised three adjacent horizontal bars, each 1 deg wide, but presented stimultaneously. The outer two bars were of fixed luminance equal to that of the metacontrast mask, while the central bar could be varied under observer control.

The metacontrast stimuli to be measured comprised a 1 deg horizontal target bar, and two adjacent 1 deg horizontal mask bars, presented with an asynchrony of 40 ms. The luminance increment of both target and mask was varied in logarithmic steps from 400 cd m^{-2} to 20 cd m^{-2}, always superimposed on a 250 cd m^{-2} background. The luminance of the outer bars of the matching standard varied with that of the metacontrast bars, to emulate the contrast conditions during metacontrast.

Observers adjusted the luminance of the matching bar until it appeared to have the same luminance as the target metacontrast bar. Once satisfied with the match, the observers pressed a response button, whereupon the computer recorded the matched level of brightness and presented the next trial. Ten settings were made for each observer, all within one randomly interleaved session.

The amount of metacontrast at each luminance level was taken to be the ratio of the apparent (matched) luminance of the target, to its physical luminance. Where luminance decrement was required for the match (that is, the apparent luminance was less than the background luminance, implying an apparent contrast reversal) the ratio is considered negative.

2.4 *Detection thresholds*

To determine the amount of summation between the target and mask, detection thresholds were measured for the target and mask when presented independently, and compared with thresholds for when the two were presented together at various asynchronies. In all cases the measure was of the minimum luminance required for the observer to see 'something on the screen': he did not have to report on whether he thought it was the target or the mask.

Because of the small predicted differences in threshold, and the possibility of experimenter bias, a forced-choice procedure was used: stimuli (accompanied by an audible tone) were presented either 4 deg above or 4 deg below the fixation point (at random). The observers guessed at its position by pressing the appropriate response button.

The procedure was identical to that described by Burr (1980a). Trials were selected at random from nine possible conditions (seven asynchronies, and the two stimuli presented alone) and displayed with various luminance increments near threshold. The luminance was determined by a staircase for each condition which homed in near threshold and then jittered around that value (over a range of ~0.3 log units). The staircase served only to select luminance values near threshold, response to which yields maximum information for threshold estimation The staircase itself did not predict threshold. One hundred trials were collected for each condition in each session.

The proportion of correct responses was then calculated for each contrast of each condition, and the results fitted to the equation:

$$p_i = 1 - \tfrac{1}{2}\exp\left(-10^{\beta(x_i - T)}\right), \qquad (1)$$

where x_i is the log luminance increment, p_i is the proportion correct at that luminance, T is the threshold, and β is a parameter which determines the slope of the probability-of-seeing curve. Equation (1) is one version of a distribution studied by

Weibull (1951) and commonly used to fit probability-of-seeing data (see, for example, Watson 1979). In its present form it gives a threshold which yields a probability of seeing of 82%.

Five sessions were run for each observer, yielding five separate estimates of threshold, from which the mean and standard error were calculated. It also yielded an estimate of the slope of the probability-of-seeing functions, β, which predicts the amount of probability summation.

3 Results

3.1 *General observations*

Metacontrast is easily obtained under photopic conditions. When a briefly-presented single bar of moderate contrast (33%) is straddled after a suitable interval (say 40 ms) by a double bar, the luminance of the first bar seems to be considerably attenuated. Furthermore, the area of screen on which the first bar had been displayed seems to be slightly darker than the rest of the background screen.

When the presentation order is reversed, the single bar predominates. However, the attenuation of apparent luminance of the double bar is less than that observed for the other presentation order.

In both cases, there is a weak sensation of motion accompanying the display [as observed by Schiller and Smith (1966) and Kahneman (1967)]. Either the single bar seems to 'expand' into the double bar, or the double bar 'shrinks' into the single bar. Metacontrast does not require that the second stimulus be a flanking double bar. As Stigler (1913) originally showed, the brightness attenuation can be also induced with a single adjacently positioned stimulus. Under these conditions, the sensation of motion is far stronger.

3.2 *Photopic metacontrast function*

Figure 1 shows the metacontrast functions for the two observers, measured with bars of 500 cd m^{-2} against a uniform background of 250 cd m^{-2}: that is, at a contrast of 33%. These curves have a similar form to previous measurements (see, for example, Alpern 1953), but peak at a lower latency. The difference in peak asynchrony presumably results from the higher luminance used in these experiments, which is well known to produce a faster visual response (see, for example, Van Ness et al 1967). This point is addressed in section 4.

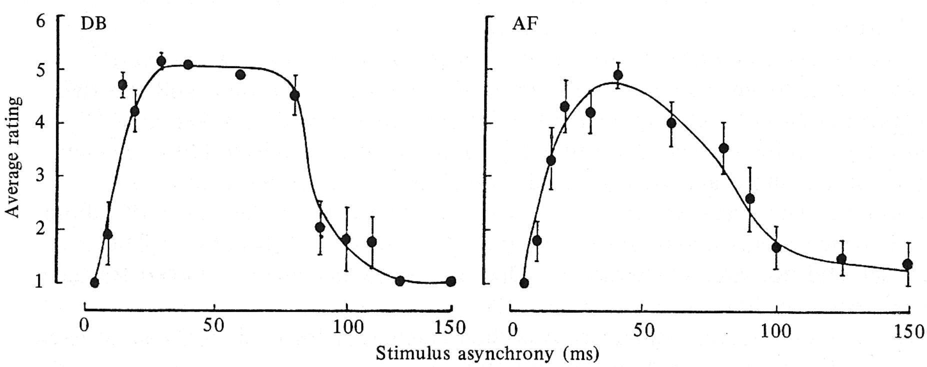

Figure 1. Rated metacontrast for the two observers, as a function of stimulus onset asynchrony. Both curves rise to a peak at ~30–50 ms and fall away to a rating of 1 (no attenuation of apparent luminance) after 100 ms. These curves have the same general inverted U-shaped form as previous measurements (for example, Alpern 1953), but peak at lower stimulus latencies. This presumably results from the higher luminance used in these experiments.

3.3 *Effect of contrast*

As the major experiment of this study was at threshold, it is necessary to establish that metacontrast can be obtained at, or at least near to, threshold. To do this, the strength of metacontrast was measured as a function of stimulus contrast, to see if there is any tendency for the effect to diminish near threshold. Observers were required to match the luminance of a bar of a matching stimulus to the apparent luminance of the target bar of the metacontrast display (see section 2.3 for details).

The results of these measurements are reported in figure 2. The strength of metacontrast is taken to be the ratio of the luminance increment of the matching bar to the real luminance increment (a matched decrement is expressed as a negative increment), and is plotted against the real luminance increment of the bar. The arrows at the left of the abscissa show the threshold for detecting the display (calculated by the forced-choice technique described in section 2.4).

For both observers, the average ratio is negative (about -0.1) and virtually constant. This means that the part of the screen where the target bar appeared was seen to be dimmer than the background (as a luminance decrement or contrast reversal), and that the magnitude of the decrement was proportional to the luminance of the mask bars.

This result shows that metacontrast can be obtained at equal strengths at all contrasts and that there is no measurable tendency for the effect to vanish at threshold (but see also Reeves 1981).

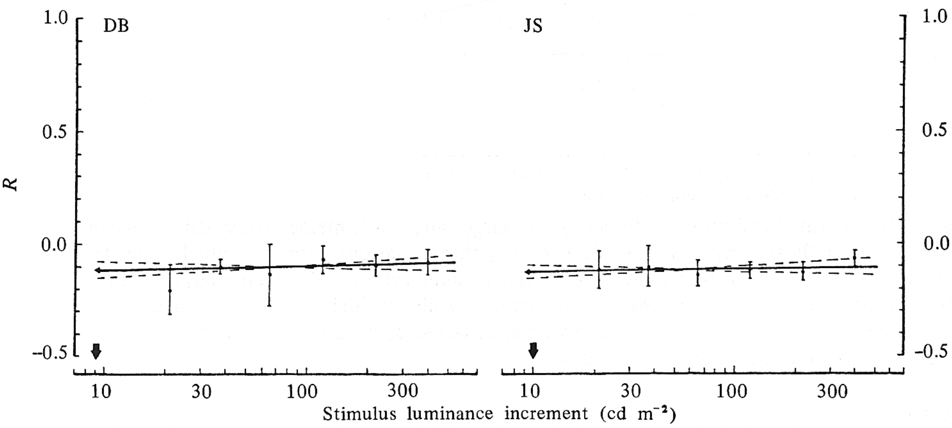

Figure 2. The effect of contrast, or luminance increment, on the strength of metacontrast. Each point represents the ratio of the apparent luminance to the actual luminance of the stimulus, R (with the bars indicating standard error). The heavy line represents the result of weighted least-squares fit (with the broken lines indicating the error range of the slope of the fit). As is evident, there is no tendency for the reduction in apparent luminance to diminish at low contrasts, even near threshold (shown by the arrows).

3.4 *Detection thresholds*

Detection thresholds were measured by means of the forced-choice technique described in section 2.4 As mentioned earlier, these measurements are not of the apparent luminance of the target but of the threshold when test and mask are presented together. The purpose of this experiment was to see how the energies of the two stimuli interact at the detection stage.

Figure 3 shows the results, as values of log increment luminance thresholds for the target and mask when presented in isolation (indicated by the arrows) and when presented together at various temporal offsets.

When presented in isolation the mask was slightly more visible (by ~0.04 log units) than the first single bar stimulus (see arrows of figure 3). This small difference in threshold can probably be put down to spatial probability summation, which favors the larger second stimulus (Sachs et al 1971)(1).

The other points indicate the thresholds for detecting the combined target and mask presentation. At all offset intervals, the threshold for the composite stimulus is less than that for either stimulus presented in isolation. The enhancement of sensitivity is greatest at asynchronies of 20–50 ms, dropping off at shorter or longer latencies.

At 200 ms (where the two stimuli are seen as separate identities) and again at 0 ms (where a single broad bar is seen) the enhancement drops to about 0.05 log units, more or less what one may expect from probability summation over time and space. At the optimal asynchronies, however, the enhancement for both observers is about 0.17 log units (about 50%), half the target energy combined with one masking bar, and the other half with the other.

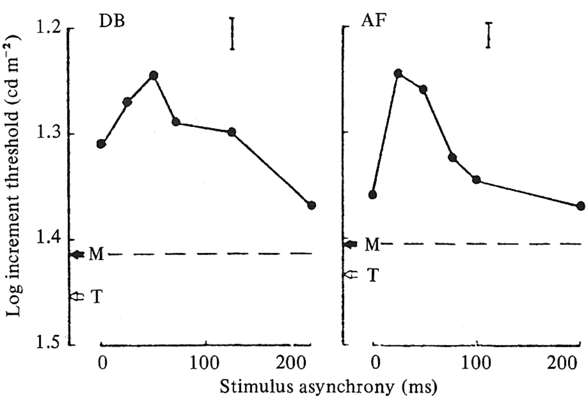

Figure 3. Increment thresholds for detecting the target and mask metacontrast stimuli when presented alone (indicated by arrows on left) or together at various stimulus asynchronies (points on the curves). The vertical bars indicate the average standard error for each measurement. The results show that sensitivity for seeing the two stimuli is always higher than that for seeing either stimulus alone, and that this sensitivity is maximal at latencies of about 30 ms, the optimal latencies for maximum metacontrast masking.

4 Discussion

The summation results speak clearly against an inhibition explanation of metacontrast, at least at threshold. Were the target inhibited by the mask, it could not be expected to contribute to the detectability of the two presented together. Figure 3 shows that not only does the target enhance detectability of the composite, but that the maximum enhancement occurs at the same temporal intervals which yield maximum metacontrast 'masking'.

The results do, however, favour a 'fusion' process in metacontrast (Fehrer 1966; Stoper and Banffy 1977).

It is interesting to speculate why fusion should occur. As metacontrast never occurs under normal conditions, it is safe to assume that it is a by-product of some more fundamental process, rather than a specific design feature. One candidate process is the motion system. A motion system necessarily consists of at least two spatially separated subunits whose outputs are combined with a temporal asynchrony (see, for example, Reichardt 1961; Barlow and Levick 1965). Detectors with these characteristics could not fail to be stimulated by the metacontrast paradigm.

(1) See Appendix.

Furthermore, if such detectors were stimulated by both the target and the mask of metacontrast, they would yield a stronger response than if stimulated by the mask alone. That is, they would sum the two stimuli.

The human motion system is known to summate energy of moving stimuli, in the form of both dots and gratings (Burr 1981). Summation for gratings is strongest when they drift at a temporal frequency near the preferred temporal frequency of the visual system, and is probably a direct consequence of the temporal tuning of motion detectors (Burr 1981). Summation also occurs with counterphased gratings, to the same extent as for drifting gratings (Burr, unpublished data). As counterphased gratings can be mathematically decomposed into two gratings drifting in opposite directions, and their sensitivity is well predicted by this decomposition (Levinson and Sekuler 1975), it is likely that counterphased gratings are detected by the motion system.

Metacontrast stimuli could be described as spatially and temporally curtailed counterphased gratings: they approximate one-and-a-half spatial cycles of square-wave grating, counterphased abruptly for one temporal cycle[(2)]. One may therefore expect them to stimulate (to some extent at least) temporally tuned mechanisms, and that these mechanisms would summate the target and mask stimuli. Furthermore, one could expect the optimal asynchrony for summation to be that with a fundamental period of oscillation equal to the preferred temporal frequency of motion detectors, about 10 Hz at the luminance used here (see, for example, Burr and Ross 1982; Anderson and Burr 1984). That is, one would expect an asynchrony of 50 ms to yield maximum summation. The results of figure 3 are not inconsistent with this prediction.

At lower luminances, the optimal temporal frequency decreases, to ~4 Hz at about 1 cd m^{-2} (see, for example, Van Ness et al 1967). At this luminance one would expect maximal summation at around 125 ms, the asynchrony that yields maximal metacontrast at low luminances (Alpern 1953). It would be interesting to measure summation at this luminance.

Assuming for a moment that temporally tuned detectors are in some way implicated in metacontrast, why should they lead to a decrease in the apparent luminance of the target? A photographic camera with a shutter speed of 125 ms will register accurately both target and mask metacontrast stimuli at all asynchronies up to 125 ms. The same camera will register considerable smear with moving targets (Burr 1980b). However, our motion detectors, which also have a 'shutter speed' (summation time) of ~125 ms, do not report significant smear (Burr 1980b). If motion detectors are implicated in metacontrast, it is plausible that the same process which ensures smearless perception of moving targets will also be acting during metacontrast. Here, the absent 'smear' corresponds to the first presented stimulus, the target. It has been argued elsewhere (Burr and Ross 1984a; 1984b; see also Fahle and Poggio 1981) that the lack of motion smear is a direct consequence of the spatiotemporal tuning of motion detectors, and requires no active deblurring process. Inhibition plays a part in these models, but the inhibition serves to sharpen the motion tuning, not eliminate the smear.

The reader may reasonably ask why, if metacontrast activates the motion system, do we not see motion? While many investigators have observed that a sense of motion often accompanies metacontrast (for example, Schiller and Smith 1966), it does not necessarily do so (Stoper and Banffy 1977). This does not, however, exclude the possible involvement of motion detectors in metacontrast. Counterphased gratings

[(2)]This is not quite true as the bars are briefly pulsed, but this has little effect on the present discussion. This pulsing merely introduces some higher temporal frequencies.

sometimes yield a sense of apparent motion, but sometimes do not, depending on their spatial and temporal frequency (eg Kelly 1966); yet few would argue that motion detectors are not activated in some way by counterphased gratings. There is no immediate reason to assume that a sense of directed motion is a necessary by-product of motion (or, more generally, spatiotemporally tuned) mechanisms. What determines the resultant sense of motion for complex, bidirectional stimuli is an interesting question in its own right, but it would be naive to assume that if no motion is observed, motion detectors have not been stimulated.

A connection between motion and metacontrast has often been mooted (Fehrer 1966; Schiller and Smith 1966; Kahneman 1967; Didner and Sperling 1980). Alpern (1953) also suggested that metacontrast masking may be instrumental in deblurring motion smear. The results reported here, viewed in the light of recent studies on summation and movement and of recent models of motion smear, support the notion of a fusion process, and are consistent with the idea that motion and metacontrast are connected.

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APPENDIX

Probability summation

If two targets are detected by independent mechanisms, a small summation effect, called probability summation, should result from the probabilistic nature of detection (Sachs et al 1971). The predicted amount of summation is readily calculated if one accepts that the Weibull function [equation (1)] is a reasonable approximation to the psychometric detection function (Watson 1979).

From equation (1), the probability, P_i for detection of at least one of j independently detected targets will be given by

$$\begin{aligned} P_i &= 1-\tfrac{1}{2}\prod_{j=1}^{n} \exp\left(-10^{\beta(x_i-T_j)}\right) \\ &= 1-\tfrac{1}{2}\exp\left(-\sum_{j=1}^{n} 10^{\beta(x_i-T_j)}\right) , \end{aligned} \tag{A1}$$

where x_i is the log luminance for the combined presentation, and T_j is the threshold log luminance for each individual target. As before, β gives the slope of the function. When $P_i = 0.82$, x_i will define threshold log luminance. By inspection of equation (A1), it follows that for $P = 0.82$,

$$\sum_{j=1}^{n} 10^{\beta(x_i-T_j)} = 1. \tag{A2}$$

Solving for x in equation (A2), we obtain

$$x_i = -\frac{1}{\beta}\lg\left(\sum_{j=1}^{n} 10^{-\beta T_j}\right) . \tag{A3}$$

The average values of β (which was free to vary in the curve-fitting procedure) were 4.2 for subject DB and 4.5 for subject AF. From figure 3, the values for log target threshold are 1.41 and 1.41 (for DB and AF, respectively) and those for log mask threshold are 1.45 and 1.44. Solving equation (A3) for x_i gives predicted log thresholds for combined target and mask presentation (given only probability summation) of 1.36 for DB and 1.35 for AF. This value agrees well with measured values at asynchronies of 0 and 200 ms (where one expects no physical summation), except perhaps for DB at 0 ms.