Research Report

STIMULUS-ONSET ASYNCHRONY IS NOT NECESSARY FOR MOTION PERCEPTION OR METACONTRAST MASKING

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Abstract—*Coherent directional motion is seen if a translated image is displayed in two sequential frames (F1 and F2). In a related paradigm—metacontrast masking—the mask (F2) reduces the visibility of the target (F1). Although strict temporal succession has been considered essential in both paradigms, we obtained both coherent motion and metacontrast masking with simultaneous onsets of F1 and F2, provided that F2 outlasted F1. Computational models of motion sensors are inherently capable of explaining these results, but inhibitory theories of metacontrast masking are disconfirmed.*

Visual stimuli shown in rapid sequence across neighboring spatial locations can give rise to at least two classes of well-known perceptual phenomena: apparent motion and metacontrast masking. Coherent directional motion is seen if an image (e.g., a group of random dots) is displayed in two sequential frames, F1 and F2, wherein F2 is a translated version of F1. In metacontrast masking, F1 is a target (e.g., a disk) and F2 is a mask whose contours are adjacent to the target (e.g., an annulus). Masking occurs if the visibility of the target is reduced by the trailing mask.

There has been general agreement that strict temporal succession is essential in both paradigms (Kahneman & Wolman, 1970; Stigler, 1910; Wertheimer, 1912). That is, for motion (or metacontrast) to be perceived, F1 must precede F2 by some temporal interval. Estimates of the optimal interval vary, but tend to be in the range of 50 to 150 ms (Alpern, 1953; Breitmeyer, 1984). The required temporal separation can be achieved by inserting a blank interval between F1 and F2 (interstimulus interval, or ISI) or, with ISI equal to zero, by displaying F1 continuously until the onset of F2. In either case, the crucial variable is held to be not ISI but stimulus-onset asynchrony (SOA), the temporal interval between the two onsets. Because of its stability, this temporal relationship has come to be known as the *onset-onset law* (Kahneman, 1967) or *SOA law* (Breitmeyer, 1984).

Contrary to the SOA law, we have found that apparent motion and metacontrast masking can be obtained with simultaneous onsets of F1 and F2 (i.e., with SOA equal to zero), provided that F2 outlasts F1. The motion outcome, reported in Experiment 1, can be explained in terms of distribution of energy in the spatiotemporal spectrum. The metacontrast results, reported in Experiment 2, cannot be explained in terms of inhibitory interactions between target and mask, as posited by extant inhibitory models.

EXPERIMENT 1: MOTION IS SEEN WITH SOA EQUAL TO ZERO

Method

Data were collected from two observers: a research assistant and one of the authors. Both had normal vision with corrective lenses. The observer sat in a dimly lit room and viewed a fixation cross at the center of the screen from a distance of 57 cm, set by a headrest.

All displays were presented on a Tektronix 608 oscilloscope equipped with P15 phosphor. The intensity gain of the oscilloscope was calibrated with a standard test patch to a luminous directional energy per point of 0.0681 cd-μs (Sperling, 1971). Stimulus brightness was equated across exposure durations using the procedure described by Di Lollo and Finley (1986).

The stimuli were 40 random dots contained in each of two frames (F1 and F2) displayed in a 2° × 2° area centered on the screen. F2 contained the same dots as F1, displaced uniformly to the left or to the right by 10 min arc. Upon a button press by the observer, the fixation cross disappeared and all 80 dots in F1 and F2 were displayed simultaneously for 1 ms. Then the 40 dots in F1 were turned off and those in F2 remained in view for an additional period of 0, 1, 5, 10, 15, 20, 30, 40, 80, 120, 160, 200, or 240 ms. Observers indicated the direction of motion (left or right) by pressing the appropriate button in a hand-held box. Each of the 13 durations of F2 was presented 10 times in random order in each of 10 sessions. This yielded a total of 100 estimates per condition.

Results

Results for both observers are shown in Figure 1. As might be expected, no motion was ever seen when F1 and F2 ended simultaneously. Rather, observers saw a field of static pairs of dots (as illustrated in Fig. 2a) that seemed to last far longer than 1 ms. However, perception of directional motion developed rapidly as the exposure duration of F2 was increased. At the longer durations of F2, static dots were never seen: Observers (and casual visitors in the laboratory) saw only dots in smooth, coherent motion.

Very brief stimuli are not essential for seeing motion under conditions of simultaneous onset of F1 and F2: When we increased the duration of the simultaneous portion of the display beyond 100 ms, good, if jerky, motion remained visible, provided that F2 outlasted F1 by a perceivable margin.

Discussion

Even though the data in Figure 1 contradict the SOA law, it can be shown that just such a pattern of results is predicted

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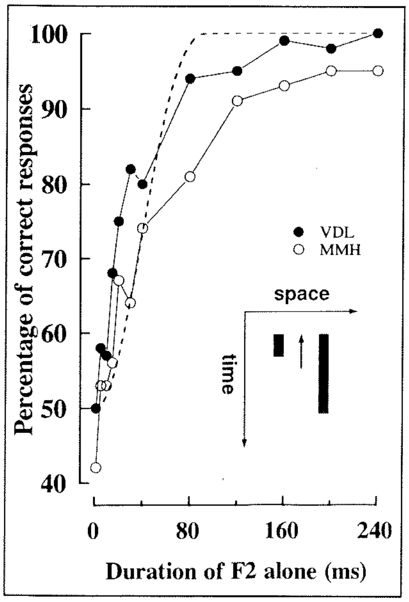

Fig. 1. Results of the motion experiment. The continuous lines show the percentage of correct responses as a function of the duration of the trailing display for two observers. The inset and the segmented line are explained in the text.

by extant models of motion perception. One way in which the temporal sequence of stimulation employed in the present work can give rise to a motion signal is by means of the peripheral motion-sensing mechanism illustrated in Figure 2 (Reichardt, 1961). A formal version of the qualitative account illustrated in Figure 2 can be developed from Watson's (1990) analysis based on quadrature models of motion sensing. In essence, it can be shown that two stimuli with simultaneous onsets but asynchronous terminations yield distributions of energy in the spatiotemporal spectrum that are unbalanced in much the same way as the distributions yielded by more conventional sequential motion stimuli.

Computer simulations were done using several models of motion sensors. The segmented line in Figure 1 shows the peak response of the motion sensor proposed by Adelson and Bergen (1985) with a value of $k = 0.05$. Peak response was defined as the strongest response of the motion sensor over time, normalized to responses made at long durations of F2. The inset in Figure 1 shows the space-time diagram of one pair of dots formed by a dot in F1 and the corresponding dot in F2. The arrow in the inset points to the sensor's center.

The simulation shows that the sensor can generate a directional motion signal even if SOA is equal to zero, provided that one input outlasts the other. Virtually identical results are obtained with a Reichardt sensor and an appropriate temporal filter. An even better fit is obtained if populations of motion sensors are considered (Adelson & Bergen, 1985; Bischof & Di Lollo, 1990; Cavanagh & Mather, 1989).

EXPERIMENT 2: METACONTRAST OCCURS WITH SOA EQUAL TO ZERO

Simultaneity of onsets plays homologous roles in motion perception and metacontrast masking. This was shown in Experiment 2, which was a virtual replication of Experiment 1, with the dots in F1 and F2 replaced by stimuli commonly used in metacontrast masking.

Method

Experiment 2 was the same as Experiment 1 except for the following details. The target stimulus was a 2° square outline displayed in the center of the screen, with a 20-min arc gap in the center of a randomly chosen side. The masking stimulus was a slightly larger square outline with a 20-min arc gap on each side. The separation between target and masking contours was 10 min arc. The stimuli are shown in the inset of Figure 3. Upon a button press by the observer, target and mask were displayed simultaneously for 1 ms. Then the target was turned off

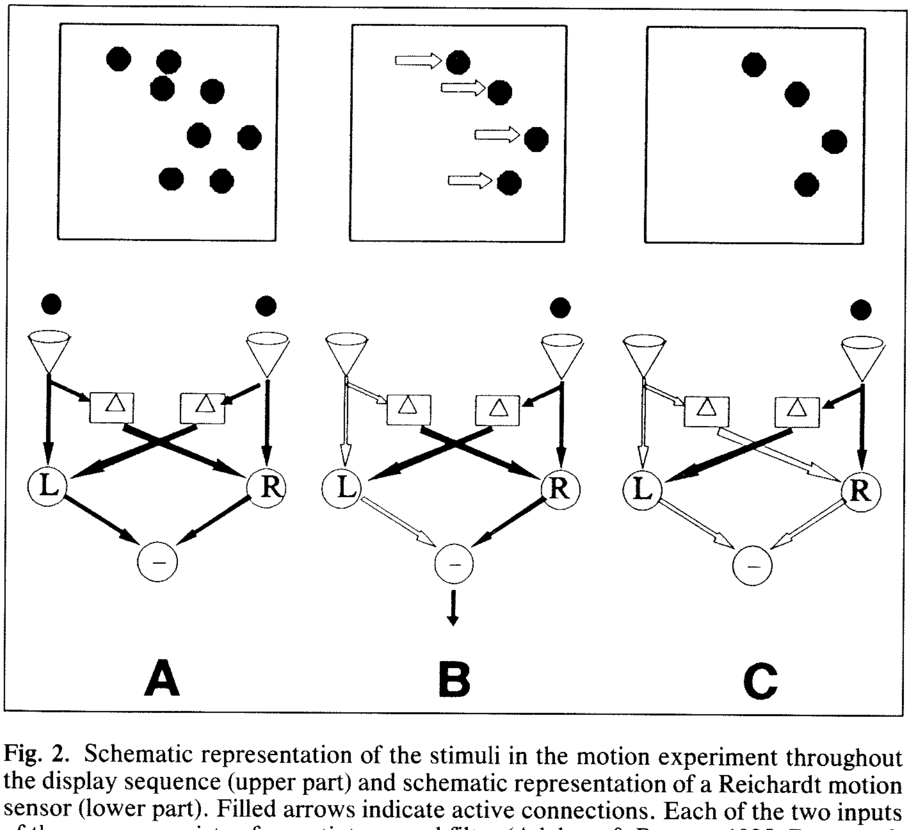

Fig. 2. Schematic representation of the stimuli in the motion experiment throughout the display sequence (upper part) and schematic representation of a Reichardt motion sensor (lower part). Filled arrows indicate active connections. Each of the two inputs of the sensor consists of a spatiotemporal filter (Adelson & Bergen, 1985; Dawson & Di Lollo, 1990; van Santen & Sperling, 1985). Two mirror-symmetrical correlators (L and R) multiply the output of one filter by the delayed (Δ) output of the other and provide input to the final stage (−), where the two products are subtracted one from the other. There is no imbalance in level of activity between left and right motion channels either during the period of simultaneous exposure of F1 and F2 (a) or after F2 has been on display alone for some time (c). Therefore, no motion signal is generated during these periods. However, when F1 is turned off, an imbalance occurs for the duration of the sensor's delay (Δ), and a right-motion signal is generated (b).

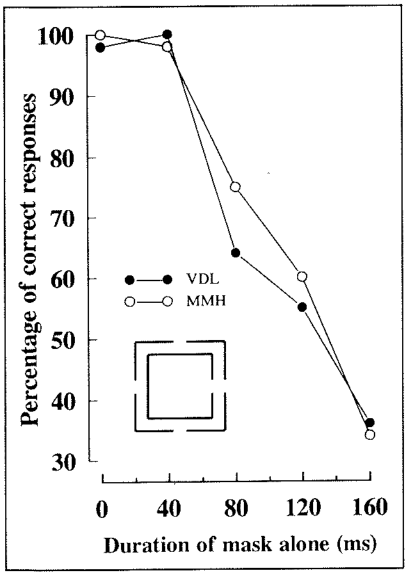

Fig. 3. Results of the metacontrast experiment. The lines show the percentage of correct responses as a function of mask duration for two observers. The inset shows the target and the mask.

and the mask remained in view for an additional period of 0, 40, 80, 120, or 160 ms. Observers indicated the side of the target that contained the gap by pressing the appropriate button in a hand-held box.

Results

The results, shown in Figure 3, are remarkably similar to the descending portion of the U-shaped curve traditionally obtained in studies of metacontrast masking (Breitmeyer, 1984; Kahneman, 1967). Performance does not recover in the present paradigm because there is no mask-free period corresponding to the long SOAs in the traditional paradigm.

Discussion

Inhibitory theories of metacontrast masking cannot account for the results in Figure 3 because all such theories were designed explicitly to exclude masking effects at SOAs equal to—or slightly greater than—zero (Alpern, 1953; Breitmeyer & Ganz, 1976; Matin, 1975; Weisstein, Ozog, & Szoc, 1975). This was done to accommodate the most salient finding in metacontrast masking, namely, that optimal masking occurs not at an SOA of zero but at much longer SOAs.

Several mechanisms of inhibition have been proposed, such as slow excitatory and fast inhibitory pathways in a neural network (Weisstein et al., 1975) or fast transient responses that inhibit slow sustained activity (Breitmeyer & Ganz, 1976). In every case, excitatory and inhibitory responses are held to be time-locked to stimulus onset so that, given simultaneity of onsets, inhibitory interactions between target and mask are symmetrical, and no masking is generated. In this fashion, masking is predicted only when SOA exceeds a specified minimum.

Contrary to predictions from inhibitory theories, Experiment 2 shows that masking can indeed be obtained with SOA equal to zero, provided that the mask outlasts the target by a perceivable margin. Earlier failures to obtain masking at zero SOA occurred because, in every case, target and masking stimuli not only started but also ended together. As we explain below, this procedure failed to provide the conditions necessary for reducing the visibility of the leading stimulus. Thus, SOA emerged as the crucial variable, the SOA law was asserted, and models were developed to suit the critical temporal asynchrony. But the present findings call into question the tenability of the SOA law and, *a fortiori*, the tenability of theories based on that law.

Unquestionably, onset-locked inhibition is ruled out as a masking agent by the outcome of Experiment 2. However, before inhibition can be dismissed as a significant factor in Experiment 2, an alternative source of inhibitory activity must be considered: the OFF response triggered by the termination of the masking stimulus.

An explanation in terms of OFF responses requires two stipulations. First, it is known that the visibility of a brief target is reduced if it is displayed just before the termination of the masking stimulus (Crawford, 1947). An account of this effect has been offered in terms of transient-on-sustained inhibition: The transient activity triggered by the mask's offset inhibits the ongoing sustained activity of the target, thus reducing its visibility (Breitmeyer & Kersey, 1981). Second, it is known that very brief stimuli do not produce distinct OFF responses; fully developed OFF responses are obtained only with exposure durations of 40 ms or longer (Ikeda & Boynton, 1965; Servière, Miceli, & Galifret, 1977). On these premises, it could be argued that the masking obtained in Experiment 2 (Fig. 3) could have been due to inhibition of the sustained activity of the target by the transient activity triggered by mask offset.

Although plausible, this option is not tenable. The reasoning is straightforward: To be effective, the transient response produced by the offset of the mask must occur while the sustained activity of the target is still ongoing. The later the masking transient occurs with respect to the onset of the target's sustained activity, the less effective it will be as a masking agent. At the limit, were the mask to terminate after the target's sustained activity has subsided, no reduction in the target's visibility should be expected. Thus, increasing the temporal interval between onset of the target and offset of the mask (as was done in Experiment 2) should result in rapid development of masking (as the mask's OFF transient becomes synchronous with the target's sustained activity) followed by progressive recovery as the offset of the mask is delayed beyond the period of the target's sustained activity. No such recovery from masking is evident in Figure 3. Indeed, the strongest masking was obtained at the longest asynchrony between target onset and mask offset (161 ms).

Nevertheless, it could be argued that an asynchrony of 161 ms might not have been sufficient for the target's sustained activity to have run its full course. To dispel any doubt on this issue, we ran a subsidiary study (otherwise identical to Experiment 2) in which the duration of the masking stimulus was 1,000 ms. The results were unambiguous: Percentages of correct responses were 31% and 27% for observers M.M.H. and V.D.L., respectively. Since a mask-free interval of 1,000 ms must be regarded as more than adequate for processing the contours of the target, the impairment in performance observed in Experiment 2 must be ascribed to factors other than inhibitory interference mediated by the mask's OFF response.

GENERAL DISCUSSION: A UNITARY ACCOUNT OF MOTION AND METACONTRAST

A comprehensive account of both the motion and the masking results can be couched readily in terms of spatiotemporal summation of energies between leading and trailing stimuli, resulting in reduced visibility of leading stimuli and enhanced visibility of trailing stimuli (Burr, 1980, 1981; Burr, Ross, & Morrone, 1986; Didner & Sperling, 1980). The possibility of energy summation in metacontrast masking has been noted earlier (Fehrer, 1966; Schiller & Smith, 1965; Stigler, 1910; Stoper & Banffy, 1977) and is supported by considerable evidence: First, spatiotemporal summation of energy in moving stimuli is known to occur at about the same temporal frequencies as optimal suppression in metacontrast masking (Burr, 1984); second, energy summation in a motion sequence is accompanied by phenomenological suppression of motion smear, which is akin to metacontrast suppression of temporally leading stimuli (Burr, 1980, 1981; Burr et al., 1986; Kahneman, 1967). Indeed, the functional significance traditionally ascribed to metacontrast suppression is that of reducing the smear—and of enhancing the visibility—of objects in motion (Alpern, 1953; Burr et al., 1986).

A common mechanism underlying the suppression of leading stimuli in motion and metacontrast is not inconsistent with the finding that, under special circumstances, masking may not be accompanied by the perception of motion (Burr, 1984; Stoper & Banffy, 1977). Nor is it surprising that, in the present work, the onset of masking (Fig. 3) occurred some 40 ms later than the onset of motion perception (Fig. 1). In both tasks, visibility of the leading stimuli diminished rapidly but progressively during a brief interval after the termination of F1. Given the different demand characteristics of the two tasks, both were performable during that brief interval.

Perhaps the most telling argument for a unitary account is that at the level of an individual motion sensor, the spatiotemporal distribution of energy produced at the sensor's site by a "motion" stimulus is often indistinguishable from that produced by a "metacontrast" stimulus. This explains why all earlier studies failed to obtain metacontrast masking at an SOA of zero: Synchronous onset and termination of target and mask failed to produce the energy imbalance required to activate the directionally tuned motion sensors (see Fig. 2) and hence failed to engage the mechanism of spatiotemporal summation that reduces the visibility of the temporally leading target.

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