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On the Relation Between Metacontrast Masking and Suppression of Visible Persistence

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Does the introduction of additional contours in a display sequence (an operation known to reduce the strength of suppression in metacontrast) also reduce suppression of visible persistence? In three experiments, duration of visible persistence was estimated by a method in which successful performance depends on the temporal integration of a pattern whose elements are displayed in two successive frames. In this procedure, the arrival of the trailing frame is known to exert a suppressive influence on the visible persistence of the leading frame. Embedding the elements of the leading frame within additional contours (a line grid) reduced the degree of suppression exerted by the trailing frame. This did not occur when the grid was part of the trailing display. We conclude that suppression of visible persistence and metacontrast masking belong to the same class of events.

Perception of a brief visual stimulus is known to continue for a short time after the physical stimulus has been turned off. This effect, known as *visible persistence*, enables a very brief stimulus (e.g., in the order of microseconds) to produce a perception whose duration is on the order of 100 ms or longer. This property of the visual system is of practical as well as of theoretical interest. For example, because of persistence, all parts of a TV picture appear to be simultaneously present on the screen at any given time, even though the physical display consists of a single point of light displayed successively at every screen location, each of which—through phosphor persistence—continues to emit light for less than 1 ms.

Were all stimulation to produce visible persistence lasting 100 ms or longer, however, objects in motion would invariably be seen by a stationary eye as trailing a wake of smear. That is, every successive location in the visual system stimulated by a moving object would remain active for the period of visible persistence. A wake of smear would thus be produced with a length corresponding to the distance covered by the object during the period of visible persistence. This has been graphically illustrated by Burr (1980), who trained a camera on a person walking across the field of view and left the shutter open for 120 ms. The resulting photograph revealed precisely the type of motion smear described above. The problem is that, in practice, no such smear is seen unless objects move at much higher angular velocities.

How can an observer's eye avoid the smear that is unavoidable to the camera? A solution to this problem has been proposed by Hogben and Di Lollo (1985) in terms of a process of suppression. They suggested that the visible persistence produced by a brief stimulus may be suppressed by the arrival of another stimulus close by and soon after. Couched in these terms, suppression of visible persistence is akin to the phenomenon of *metacontrast masking*, in which perception of a leading stimulus is suppressed by the arrival of a spatially adjacent trailing stimulus (e.g., Breitmeyer, 1984; Breitmeyer & Ganz, 1976).

The aim of the present research was to examine further the proposition that suppression of visible persistence and metacontrast masking belong to the same class of events. The approach was, in some sense, complementary to that adopted by Di Lollo and Hogben (1987), who showed that display conditions known to increase metacontrast masking (e.g., adaptation to higher luminance or smaller spatial separation between successive stimuli) are also effective in reducing the duration of visible persistence.

In the present work, we examine the effect of introducing additional contour lines displayed simultaneously with the leading stimuli. It is known that additional contour lines in a metacontrast display greatly reduce—and may even eliminate—metacontrast masking (Breitmeyer, 1978; Breitmeyer, Rudd, & Dunn, 1981; Stoper & Banffy, 1977; Werner, 1935). We used such contours in a two-frame sequential display designed to study the duration of visible persistence of the leading frame. We reasoned that if suppression of visible persistence and metacontrast masking are separate expressions of the same phenomenon, then the additional contours in the display might extend the duration of visible persistence by reducing—or even preventing—its suppression by the temporally trailing frame. The outcome of the research confirmed these expectations and thus provided converging evi-

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dence in support of the proposition that suppression of visible persistence and metacontrast masking are related processing events, probably based on lateral inhibitory interactions between successive stimuli.

Experiment 1

Duration of visible persistence was estimated in this study by the method of temporal integration of form parts (Coltheart, 1980; Eriksen & Collins, 1967). This method requires the synthesis of a pattern whose elements are divided randomly into two frames that are displayed in rapid succession, separated by an interstimulus interval (ISI). The pattern used in this study consisted of 24 of the 25 dots defining a 5 × 5 square matrix plotted on an oscilloscope. The observer's task was to name the matrix location of the missing dot.

To study visible persistence, the matrix was displayed in two frames of 12 dots each, chosen differently on every trial, separated by a variable ISI. Successful performance on this task depends on the simultaneous visibility of the dots in both frames: Seen separately, the two frames appear as meaningless configurations, but, when integrated, they form a regular matrix with the empty location easily detectable. As might be expected, integration is achieved easily at short ISIs, suggesting a duration of visible persistence sufficient to bridge the temporal gap. However, as the ISI is lengthened, temporal integration becomes progressively impaired until the two frames are perceived as discrete and the location of the missing dot can no longer be identified. The longest ISI at which temporal integration remains possible is taken as an index of the duration of visible persistence.

In this paradigm, the primary role of the trailing frame is to act as a temporal probe for estimating the duration of visible persistence of the leading frame. However, under some circumstances, the trailing frame can assume additional properties that may actually curtail the visible persistence of the leading frame. As noted above, Di Lollo and Hogben (1987) regarded this curtailment as a process of suppression akin to metacontrast masking and as potentially involved in the suppression of motion smear. In the present study, an operation known to reduce metacontrast masking (namely, the introduction of additional contours) was used in conjunction with the matrix-integration paradigm to determine whether the additional contours also reduced the power of the second frame to suppress the visible persistence of the first.

For this purpose, two types of displays were used. One consisted of the simple 25-dot matrix described above. The other consisted of the same dot matrix embedded within a square line-grid composed of six vertical and six horizontal lines that defined a 5 × 5 matrix of square cell. Each cell of the grid contained a dot at its center, as shown in Figure 1. The salient difference between the two types of displays is that, whereas in the gridless display adjacent dots were separated just by a blank space, in the grid display adjacent dots were separated by a blank space plus a grid line.

In suit with the paradigm's requirements, the display sequence consisted of two successive frames, whose contents were set to match the conditions found by Breitmeyer (1978) and by Stoper and Banffy (1977) to be most effective in

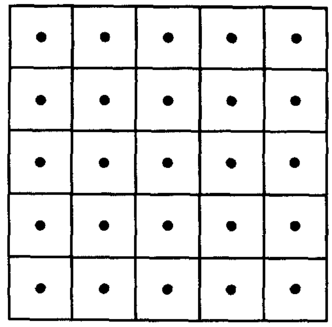

Figure 1. The 25-dot matrix embedded within the line grid.

reducing metacontrast masking, namely, simultaneous termination of target and additional contours. That is, the leading frame contained the entire line grid plus 12 matrix dots, chosen randomly on each trial; the second frame contained only the 12 complementary dots that made up the 24 dots of the incomplete matrix. In agreement with expectations, the suppressive effect of the trailing frame was found to be muted in the grid displays. An unexpected, though understandable, effect also emerged: The presence of the grid lines reduced the detectability of the empty matrix location, particularly at the periphery of the matrix. This was ascribed to the effect of lateral masking (e.g., Wolford & Chambers, 1984), which could be partialed out of the results to reveal the unconfounded effect of the grid on duration of visible persistence.

Method

Subjects. Two of the authors and 1 female student, naive as to the purpose of the study, served as observers. All had normal or corrected-to-normal vision.

Visual displays. All stimuli were displayed on a Hewlett-Packard 1332A oscilloscope equipped with P15 phosphor. At a viewing distance of 57 cm, set by a headrest, one side of the 8 × 8-cm display surface subtended a visual angle of 8°. All stimuli were displayed in the center of the screen.

There were two types of displays: *gridless* and *with grid.* The gridless display consisted of 24 of the 25 dots defining a 5 × 5 square matrix, plotted at an intensity of 64 cd/m^2 on a background of less than 1 cd/m^2. Spatial separation between adjacent dots was 0.5°. Because the diameter of a single dot was just over 1 min, the total matrix subtended a visual angle of just over 2.0°. The display with grid consisted of the same dot matrix embedded within a square line-grid as in Figure 1. One side of the grid subtended a visual angle of 2.5°, and the separation between adjacent grid lines was 0.5°. Thus the separation between each matrix dot and the nearest grid line was 0.25°. The thickness of the grid lines was just over 1 min, and their intensity was 37 cd/m^2.

Design and procedure. Observers sat in a dimly lit room and viewed the display binocularly with natural pupils. Four fixation points of low intensity defined a 1° square area in the center of the screen. The sequence of events for gridless displays was as follows. Upon a button-press by the observer, 12 dots were displayed for 20 ms. Next, there was an ISI of either 0, 20, 40, 60, 80, or 120 ms, during which the screen remained blank. Finally, the remaining 12 dots were displayed for 20 ms. The observer then identified the location of the missing dot (guessing if not sure) by encoding its matrix coordinates in a five-button response box. The 12 dots in each frame were chosen randomly on every trial from the 25-dot pool, with the restriction that, within each experimental condition, the empty matrix location appeared equally often in each of the 25 possible locations.

Displays with grid were the same as gridless displays, except that the temporally leading frame contained the entire line grid in addition to the 12 matrix dots. Thus, a with-grid display sequence consisted of a 20-ms exposure of the grid lines combined with the leading 12 dots, an ISI, an a 20-ms exposure of the trailing 12 dots without grid lines.

An experimental session consisted of 150 randomly ordered trials comprising 25 presentation of the dot matrix at each of the six ISIs. The 150 trials occurred in a different random order in each session and were completed in about 10 min. Either gridless or with-grid stimuli were shown in any given session. Each observer served in a total of eight sessions, four in the gridless and four in the with-grid conditions, in an alternating sequence, yielding a total of 100 observations at each ISI for each of the two grid conditions.

Results and Discussion

Figure 2a (top panel) shows the percentage of correct responses made by the 3 observers in each experimental condition. For reasons of consistency with the next two experiments, the results are expressed as a function of SOA (stimulus onset asynchrony; the time elapsing between the onsets of the two frames) rather than ISI. Each SOA is composed of the duration of the leading frame (20 ms) and the ISI.

As might be expected, SOA had a powerful effect on performance both with and without the grid. With gridless displays, performance of all 3 observers deteriorated rapidly as SOA was increased beyond 40 ms. This result is consonant both with the spontaneous decay of visible persistence during the course of the SOA and with the possible effect of metacontrast-like suppression of visible persistence by the arrival of the second frame.

Performance with the grid also decreased as a function of SOA, but to a somewhat lesser extent. A probit fit performed on the performance curves in Figure 2a for each of the 3 observers yielded σ values of 20.6, 28.5, and 23.1 for the gridless condition, and 65.1, 55.2, and 65.6 for the condition with grid. Clearly, performance dropped more slowly as SOA increased in the condition with the grid. A slower decay is precisely what might be expected if the grid lines reduced or prevented the suppression of visible persistence.

Specification of the effect of the grid, however, is not entirely straightforward. The curves in Figure 2a show evidence of at least one additional factor: In every case, performance with the grid at short SOAs was poorer than with gridless displays. We hasten to note that this impairment in performance could not be wholly responsible for the larger σ values reported here, for there is also clear evidence of *facilitation* in the grid condition at the longer SOAs (Figure 2a). Nevertheless, the lower performance level at the short SOAs must be accounted for if the effect of the grid is to be understood.

A possible reason for the impairment was suggested by the appearance of the displays. At the shorter SOAs, the two frames were seen as simultaneous rather than successive. Yet, although perceived simultaneity made the empty matrix location stand out in the gridless displays, it often produced the

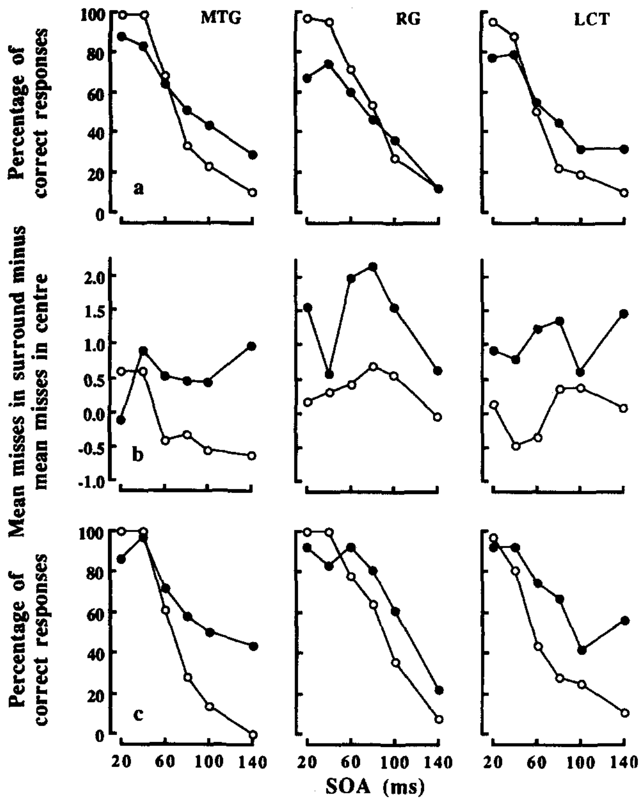

Figure 2. Percentage of correct responses made by Observers MTG, RG, and LCT in Experiment 1. In every panel, filled symbols refer to displays with grid lines, and open symbols refer to displays without grid lines. Panel a: Percentage of correct responses, separately for displays with and without grid lines, as a function of stimulus onset asynchrony (SOA) between the two successive frames. Panel b: Mean number of times the target was missed when it occurred in one of the 16 peripheral matrix locations *minus* the mean number of misses in the nine central matrix locations. Panel c: Percentage of correct responses, separately for displays with and without grid lines, as a function of SOA between the two successive frames. (The data were taken exclusively from the central nine matrix locations. Each point is based on 36 trials.)

impression of there being no empty cell at all in the displays with the grid. On the face of it, this was an instance of the phenomenon known as *lateral masking*, which refers to a reduced probability of identifying a target when it is surrounded by other contours (Bouma, 1970; Flom, Weymouth, & Kahneman, 1963; Wolford & Chambers, 1984). It has been suggested that lateral masking may be due to faulty resolution among contours falling within the same receptive field. Accordingly, masking is known to increase as the target is moved further into the periphery of the retina, where the size of the receptive fields becomes progressively larger (e.g., Wolford & Chambers, 1983, 1984). In the present context, the crowding of the display brought about by the additional contours of the grid might have produced lateral masking, particularly when the target (i.e., the empty location) fell in a peripheral—as distinct from a central—matrix location.

To examine this option, the data of each observer were reanalyzed as follows. As noted earlier, the target appeared equally often in all 25 matrix locations. Because there were 100 trials per condition, the target appeared four times in each matrix location at each combination of grid and SOA. For each grid–SOA combination, we calculated the mean number of times that the target was missed in the 16 cells on the periphery of the matrix. Next, we found the corresponding mean for the 9 central cells. Finally, we subtracted the score for the center from that of the periphery. We reasoned that if errors occurred evenly throughout the 25 matrix locations, the difference between the two scores should approach zero. On the other hand, the difference should be positive if relatively more errors were made when the target fell in the periphery, and negative in the converse case. Figure 2b shows the results of this analysis.

The evidence is unambiguous: In the gridless condition, errors tended to be made more or less evenly throughout the matrix. By contrast, in the grid displays, errors were made far more frequently at the periphery. This outcome is in agreement with expectations based on lateral masking. That is, the crowding produced by the grid lines may have reduced the probability of detecting the empty cell at the periphery of the matrix, with consequent reduction in the level of performance even at the shortest SOAs, as seen in Figure 2a.

Returning to the principal issue under investigation, it can now be surmised that the pattern of results illustrated in Figure 2a represents the combination of two effects: First, the grid lines protected the visible persistence of the dots in the leading frame from being suppressed by the arrival of the second frame, as shown by the slower decay in the with-grid as compared to the no-grid condition. Second, the lateral masking produced by the grid depressed the overall level of performance in relation to the gridless condition. On this reasoning, and on the evidence of Figure 2b (middle panel), the effect of lateral masking occurred principally in the peripheral cells of the matrix. If so, then performance in the central nine cells should be relatively unaffected by lateral masking and should reveal the effectiveness of the grid in counteracting suppression of visible persistence.

Figure 2c (bottom panel) is the same as Figure 2a, except that the data were taken exclusively from the nine central cells of the matrix. Thus, each point is based on 36 observations. Two aspects of Figure 2c should by noted. First, whereas the mean level (averaged over conditions and observers) of the gridless condition remained unchanged from that of Figure 2a (54% in both instances), the level of the condition with grid was substantially higher (54% and 70% in Figures 2a and 2c, respectively). Notably, the differences between Figures 2a and 2c in the with-grid conditions at the short SOAs were strongly reduced. Second, the differences between the conditions with and without the grid are much more in evidence in Figure 2c. That is, in every case, the curves for the conditions with and without the grid begin at about the same level but diverge markedly as SOA is increased. This pattern of results strongly suggests that visible persistence remained available for longer durations in the displays with the grid, permitting longer SOA to be bridged than in the corresponding gridless displays. In turn, this supports the proposition that the contours of the grid muted the suppressive effect of the trailing flash on the visible persistence of the first flash, much as additional contours reduce the extent of masking in a metacontrast paradigm. It should also be noted that metacontrast masking does not occur at very short SOAs but develops rapidly as SOA is increased (cf. Breitmeyer, 1984). The diverging curves in Figure 2c mirror just such temporal progression, with the differences between the pairs of curves ascribable to greater suppression in the gridless displays.

Although plausible, the preceding account of the effects of the grid in terms of the twin factors of lateral masking and reduction of suppression is somewhat ad hoc. This is remedied in Experiment 2, in which predictions stemming independently from the two factors are tested.

Experiment 2

Spatial separation between adjacent matrix dots, which was held constant in Experiment 1, was varied in Experiment 2. Three interdot separations were used: 0.3°, 0.9°, and 1.5°. The stimulus patterns thus produced ranged in overall size from being totally confined within the fovea to extending well into the periphery. As in Experiment 1, the dot matrix was displayed either gridless or embedded within a grid.

As the eccentricity of the stimuli is increased, two things are likely to happen: First, the duration of visible persistence increases (e.g., Di Lollo & Hogben, 1985) and, second, the suppression of leading stimuli by trailing stimuli—as in metacontrast masking—becomes more pronounced and occurs over greater spatial separations (Breitmeyer, 1984; Di Lollo & Hogben, 1985). These two effects work in opposition to each other so that, as eccentricity is increased, increments in visible persistence are counteracted by corresponding increments in strength of suppression.

Decoupling the two effects can be achieved by using procedures that selectively affect only one of the two factors. According to the arguments made in Experiment 1, embedding the dot matrix within a grid would constitute such a selective procedure because it would reduce suppression without affecting persistence. In the ideal case, total elimination of suppression by the grid would permit visible persistence to continue unhindered for progressively longer durations as eccentricity is increased. Also, this outcome would be in line with the thesis that additional contour lines have parallel—if not identical—effects in the present paradigm and in a metacontrast paradigm.

However, there is a complicating factor pertaining specifically to displays with the grid: namely, magnitude of lateral masking also increases with eccentricity (Wolford & Chambers, 1984). While not necessarily interfering with either persistence or suppression, lateral masking would impair performance, as was indicated in Experiment 1. What is worse, the degree of impairment would increase with eccentricity and would thus confound the effect of increased persistence. In Experiment 1, the influence exerted by lateral masking was reduced by considering only the inner nine cells of the matrix. In principle, this strategy could be used in the present study, except that not all the information that would be required to implement such procedure is currently available.

To construct a set of matrices with a constant surround/center ratio of lateral masking regardless of angular size, we would need to know the precise form of the function relating lateral masking to eccentricity. Some estimates of this function do exist, and they all show that masking increases with eccentricity (Bouma, 1970; Wolford & Chambers, 1984). However, there is a wide range in the actual numerical estimates, probably reflecting the fact that lateral masking is not a unidimensional phenomenon. One alternative would be to space the dots unevenly and to distort the outlines of the grid so as to suit the geometry of the cortical magnification factor (e.g., Pointer, 1986). However, this would entail a series of preliminary studies to arrive at a geometrical configuration that yielded no differences in errors across eccentricities. This laborious procedure, however, would hardly be justified in the present case because equalization of errors across eccentricities was not a crucial requirement of the experiment.

In the absence of any firm guidelines, the three matrices were simply scaled in size so as to maintain a constant ratio between the surrounding and central portions. The tacit assumption that masking increases linearly with eccentricity was not supported by the experimental data. Nevertheless, as will be seen, this did not affect the main conclusions drawn from the outcome of the study.

Method

Two of the 3 observers in Experiment 1 (MTG and RG) served in Experiment 2. Design and procedures were the same as in Experiment 1, except for the following. An SOA of 0 ms (simultaneous presentation of the two frames) was added to the six SOAs of Experiment 1. This made it possible to estimate the amount of lateral masking with simultaneous rather than sequential displays. There were three interdot separations: 0.3°, 0.9°, and 1.5°. These were combined with two grid conditions (gridless and with grid) to yield six experimental conditions, each with seven SOAs. The size of the grid was adjusted according to the interdot separation, so that each matrix dot fell in the center of each cell of the grid. The angular sizes of the three grids were 1.5°, 4.5°, and 7.5°, both vertically and horizontally.

Results and Discussion

Figure 3 shows the percentage of correct responses made by the 2 observers, separately for the conditions with and without the grid. The results of Experiment 1 (Figure 2a) have been entered in Figure 3 to aid comparison.

With gridless displays, performance improved with interdot separation. Taking the 50% level as a reference, the estimated duration of visible persistence was between 40 and 50 ms longer when interdot separation was 1.5° than when it was 0.3°. This outcome parallels that of Di Lollo and Hogben (1987) and extends the range of both spatial and temporal values over which the effect has been found.

Either or both of two mechanisms may underlie this effect. First, the effect may be due to increased duration of visible persistence: As interdot separation was increased, so was the eccentricity of the display, and the duration of visible persistence is known to increase with eccentricity (Di Lollo & Hogben, 1985). Second, the strength of suppression of a

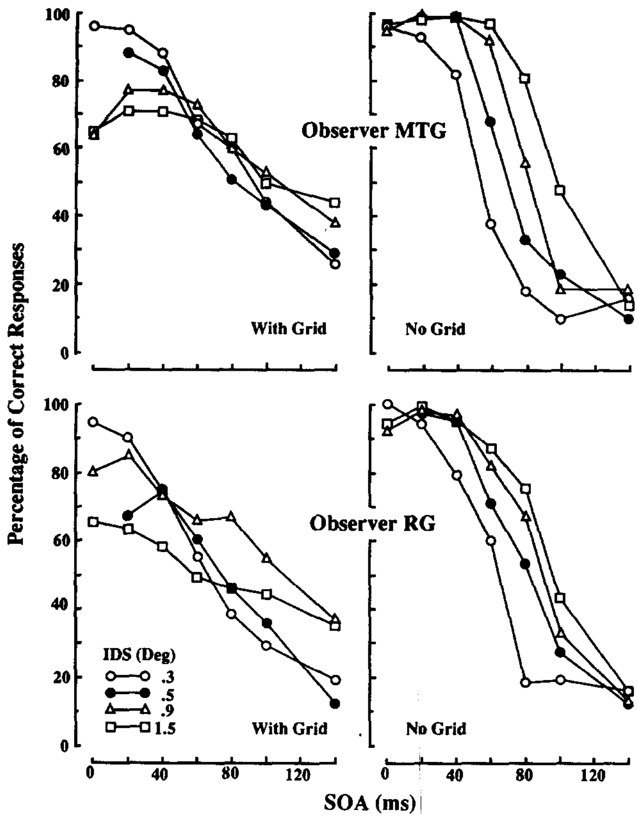

Figure 3. Percentage of correct responses in Experiment 2, separately for displays with and without grid lines, as a function of SOA and of interdot separation (IDS).

leading stimulus by a trailing stimulus—as in metacontrast masking—is known to decrease as spatial separation is increased (Breitmeyer, 1984; Di Lollo & Hogben, 1985). Thus, the progressive improvement seen in the gridless condition with increments in interdot separation (Figure 3) may be due, at least in part, to diminishing strength of suppression. Also in keeping with this result is the finding that a trailing stimulus takes a longer period of time to inhibit a leading stimulus (i.e., the latency of inhibition is longer) as spatial separation is increased (van der Wildt & Vrolijk, 1981). In the following paragraphs, we suggest that suppression probably played a prominent part in the performance decrement.

Turning to the condition with the grid, it is immediately apparent that performance declines as a function of SOA, though at a markedly slower rate than with gridless displays. Moreover, the orderly effect of interdot separation, seen in the gridless condition over the range of SOAs, is absent from the condition with the grid. To be sure, interdot separation did have an effect, but it was opposite to that found in the gridless displays and occurred only at SOAs below about 40 ms, at which the two frames were seen as perceptually integrated. At these SOAs, the level of performance became progressively lower as separation was increased (see Figure 3). This can be readily interpreted in terms of lateral masking whose strength increases with eccentricity (Wolford & Chambers, 1984).

To gauge the extent to which the conditions with the grid (left panels of Figure 3) were affected by lateral masking, we performed the type of analysis that yielded Figure 2b in Experiment 1. For each observer in each experimental condition, we calculated the mean number of times that the target was missed in the 16 peripheral as distinct from the 9 central cells of the matrix, and we subtracted the latter score from the former. A positive score indicated a propensity for missing the target when it occurred in the periphery. These data, averaged over the 2 observers, are illustrated in Figure 4.

At each interdot separation, the scores for the gridless condition were close to zero, indicating that targets were missed with about equal probability in the periphery as in the center of the matrix. By contrast, the scores for the condition with the grid were uniformly higher, indicating stronger lateral masking at the peripheral matrix locations. The magnitude of the differences increased markedly with eccentricity, suggesting that the function relating strength of lateral masking to eccentricity is curvilinear with positive acceleration, rather than linear, as we had assumed when designing the stimuli. Tests of significance were carried out on the individual scores summarized in Figure 4. In the no-grid condition, only 3 out of 42 scores (seven SOAs, three interdot separations, 2 observers) were significantly different from zero, $p < .01$.[1] Similarly, in the with-grid condition at an interdot separation of 0.3°, only 3 of the 14 scores were significant. By contrast, in the with-grid condition at interdot separations of 0.9° and 1.5°, all but 5 of the 28 scores were significantly higher than zero. In any event, the data in Figure 4 clearly suggest that the central nine cells of the matrix were less affected by lateral masking than were the peripheral cells at all interdot separations. Accordingly, as was done in Experiment 1 (Figure 2c), the percentages of correct responses were recalculated with data taken only from the nine central locations of the matrix. The recalculated results are shown in Figure 5.

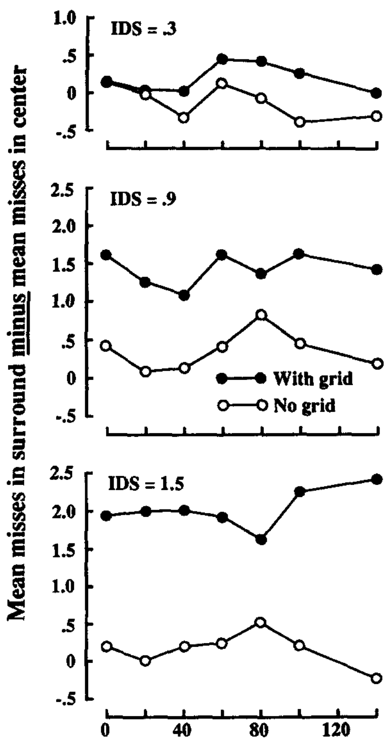

Figure 4. Mean number of times the target was missed when it occurred in one of the 16 peripheral matrix locations *minus* the mean number of misses in the nine central matrix locations, separately for each interdot separation (IDS) in Experiment 2.

A comparison of Figures 3 and 5 reveals differences that are readily detectable in the condition with the grid but not in the gridless condition. Notably, the effect attributed to lateral masking at the short SOAs in the left panels of Figure 3 is totally absent from the corresponding curves in Figure 5. Instead, the four curves are seen to fan out at the longer SOAs. This is just what might be expected if the level of each curve in Figure 3 had been increased by a value whose magnitude increased with interdot separation but remained constant across SOAs. In light of this, and of the ancillary evidence noted above, we regard lateral masking as the most likely source of the differences between the two sets of data. On this reasoning, the data in the left panels of Figure 5 must be regarded as being influenced far less by lateral masking than are the corresponding data in Figure 3.

Comparisons can now be made between the left and right panels in Figure 5 to assess the effect of the grid on visible persistence. At the short SOAs, there was no difference in performance between displays with and without the grid, confirming that the grid did not act as a source of response interference in the central matrix locations. In gridless displays, performance remained high for periods that varied with interdot separation and then dropped rapidly to a low asymptotic level. This pattern of results is in agreement with earlier investigations in which the rapid drop had been ascribed to the inhibitory effect of the second frame on the visible persistence of the first, and the ordering of the curves had been ascribed to inhibition that is both faster and more powerful at shorter interelement distances (Breitmeyer, 1984; Di Lollo & Hogben, 1987; van der Wildt & Vrolijk, 1981). By contrast, performance with the grid remained high over longer periods and declined much more gradually as a function of SOA. Most notably, the suppression that produced the rapid drop with the gridless displays was absent—or much reduced—with the grid displays.

In a nutshell, adding the grid lines to the matrix display reduced significantly the suppressive effects of the trailing frame. In turn, this permitted visible persistence to continue over longer SOAs than was possible in gridless displays. To estimate the duration of visible persistence in the two types of displays, cumulative normal curves were fitted through the

[1] The target (i.e., the empty cell) occurred in each of the 25 matrix locations four times in 100 trials; thus it occurred in the 16 peripheral locations 64 times in 100. On the assumption that misses are equally likely at each matrix location, the number of misses in the periphery follows a hypergeometric distribution $h(16/25, n)$, where n is the total number of misses.

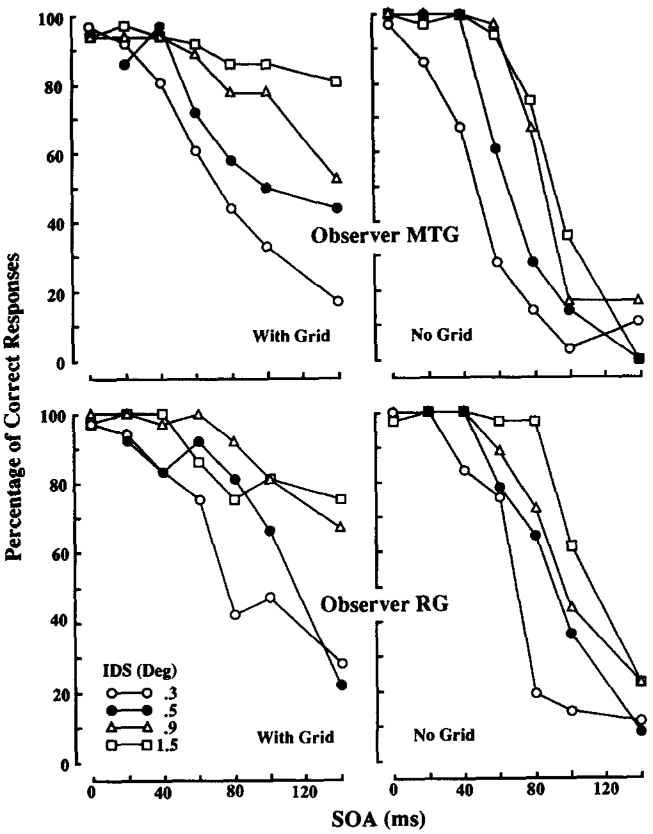

Figure 5. Percentage of correct responses in Experiment 2, separately for displays with and without grid lines, as a function of stimulus onset asynchrony (SOA) and of interdot separation (IDS). (The data were taken exclusively from the central nine matrix locations. Each point is based on 36 trials.)

data points in Figure 5 by using probit estimation procedures. The mean of each curve (the midpoint between chance level and perfect performance) was then taken as an index of the duration of visible persistence for that condition. Averaged over the 2 observers, the means for interdot separations of 0.3°, 0.5°, 0.9°, and 1.5°, respectively, were 54, 75, 90, and 101 ms for the gridless condition, and 79, 105, 150, and 216 ms for the condition with the grid. The theoretical conviction of this article is that the estimates of visible persistence obtained with grid displays were affected little, if at all, by the suppression that affected gridless displays. Hence the values obtained with gridless displays must be graded as underestimates of the natural time course of visible persistence when unhindered by suppression. It should be noted that, because of the unrecognized effect of suppression, studies that used the method of temporal integration of form parts (e.g., Di Lollo, 1977, 1980; Eriksen & Collins, 1967) probably yielded consistent underestimates of the duration of visible persistence.

Even though this interpretation of the effect of the grid is compellingly supported by the data, an alternative interpretation in terms of changes in attentional focus must be examined and discounted. This is done in the next experiment.

Experiment 3

It has been argued in the preceding sections that the grid's major role lies in reducing the amount of suppression exerted by the second frame on the visible persistence of the first. An alternative account may be couched in terms of shifts in attentional focus. To wit, it is possible that, in view of the perceptual difficulties associated with the grid displays, the observers might have resorted to ignoring the peripheral cells of the matrix to concentrate instead on the central portion. In other words, the observer may have restricted the focus of attention to encompass only the central nine dots when the matrix was embedded within the grid, while maintaining a broader focus encompassing all 25 dots in the gridless condition.

An attentional strategy of this kind would produce just the type of results seen in Experiments 1 and 2 with the data taken exclusively from the central cells (Figures 2c and 5). On this option, superior performance with the grid displays would derive not from the grid itself, but from the fact that the observer would, in effect, be dealing with only a 3 × 3 matrix (a relatively easy task) in one case, but with a 5 × 5 matrix (a far more difficult task) in the other.

Separation of the two hypotheses can be achieved by displaying the grid as part of the second, rather than of the first frame. On the present hypothesis, the dots in the leading frame would become more prone to suppression. This is so because the disappearance of the grid would no longer coincide with the termination of the dots in the leading frame (a contingency recognized by Stoper & Banffy, 1977, as producing maximum reduction of metacontrast masking). Indeed, because suppression is brought about by the contents of the trailing frame, the contours of the grid should produce even greater suppression than the trailing dots in the gridless condition because of greater spatial proximity with the leading dots. Thus, performance should be even lower than that obtained with gridless stimuli in Experiments 1 and 2.

By contrast, on the attentional hypothesis, no essential differences should be expected from the results obtained with the grid displays in the earlier experiments. Presumably, the observers' strategy in the presence of the grid would still be toward a narrowing of attentional focus.

Method

The 3 observers who served in Experiment 1 also served in Experiment 3. Displays and procedures in Experiment 3 were the same as in Experiment 1, except that the contents of the two frames were reversed. Namely, the 12 dots of the leading frame were displayed without grid lines, whereas the 12 dots of the trailing frame were displayed simultaneously with the contours of the grid.

Results and Discussion

Figure 6a (upper panel) shows the results of Experiment 3. The results of the gridless condition of Experiment 1 are also illustrated in Figure 6a to aid comparison.

Unlike the corresponding results of Experiment 1 (Figure 2a), performance in the grid condition of Experiment 3 remained lower than the level of the gridless condition through-

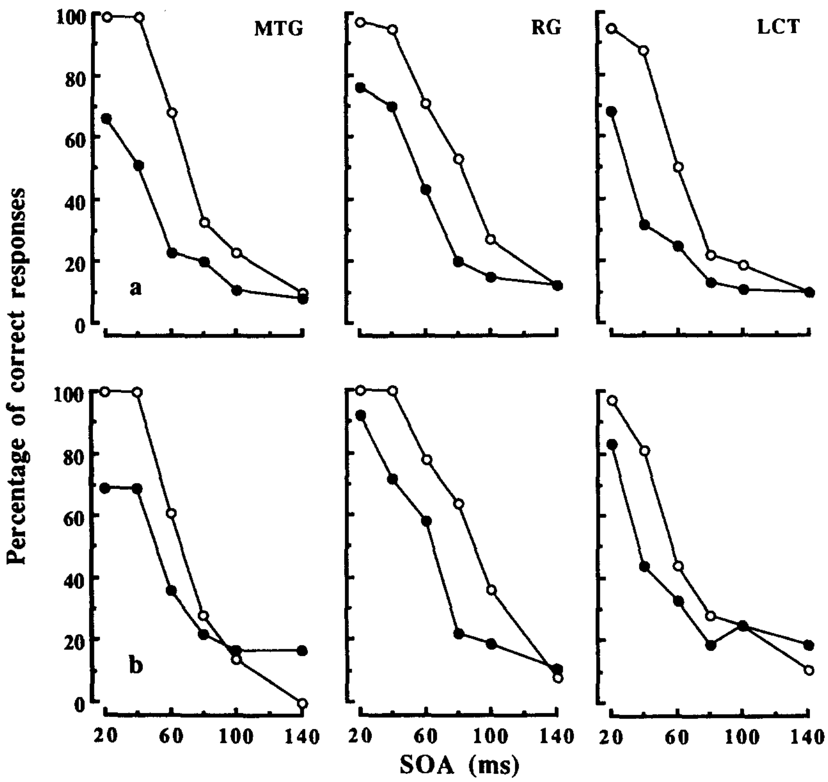

Figure 6. Percentage of correct responses made by Observers MTG, RG, and LCT in Experiment 3. In every panel, filled symbols refer to displays with grid lines, and open symbols refer to displays without grid lines. Panel a: Percentage of correct responses, separately for displays with and without grid lines, as a function of stimulus onset asynchrony (SOA) between the two successive frames. The grid was displayed in the second frame. Panel b: Percentage of correct responses, separately for displays with and without grid lines, as a function of SOA between the two successive frames. (The data were taken exclusively from the central nine matrix locations. Each point is based on 36 trials. The grid was displayed in the second frame.)

out the domain. Moreover, the differences in performance between central and peripheral cells of the matrix, so prominent in the grid condition of Experiment 2, were not found in Experiment 3. That is, there was no consistent evidence in Experiment 3 that the target was missed with greater relative frequency in the peripheral than in the central locations of the matrix. Tests of significance, similar to those done on the corresponding data in Experiment 2, showed that only 4 of the 36 scores (six SOAs, 3 observers) were significantly different from zero.

As was done in the previous two experiments, the results were reanalyzed by using only data from the central nine matrix locations. The reanalyzed data are shown in Figure 6b (lower panel). Comparison of Figure 6b with Figure 2c (and also with Figure 5) shows clearly that performance with grid displays was consistently superior to that with gridless displays when the grid was in the leading frame (Figures 2c and 5) but that the reverse was true when the grid was in the trailing frame (Figure 6b).

This evidence does not support the proposition that the grid acted to protect the visible persistence of the leading frame from suppression in Experiment 3. Nor does it support the proposition that the presence of the grid induced the observers to restrict the focus of attention so as to encompass only the central matrix locations. In either case, the relative positions of the curves in Figure 6b should have been reversed.

Rather, this pattern of results is just what was expected on the basis of suppression of visible persistence. It is notable that the addition of the grid lines to the dots of the trailing display increased the degree of suppression over what was obtained with dots alone (Figure 6b). In all likelihood, this occurred because the spatial separation between the elements in the leading frame and the closest elements in the trailing frame was halved by the addition of the grid lines to the trailing frame, and, as noted above, suppression is known to increase with spatial proximity (Breitmeyer, 1984; Di Lollo & Hogben, 1985).

In a genera sense, the outcome of this study indicates that the inclusion of additional contours in the display sequence is not sufficient, per se, to produce the improvements in performance seen in Experiments 1 and 2. Indeed, the additional contours have opposite affects when added to the leading frame than when added to the trailing frame.

Parallels between the present results and the outcome of a metacontrast experiment by Breitmeyer (1978) must be noted. As well as presenting the target and the mask, Breitmeyer displayed additional stimuli either simultaneously with the target (corresponding to the dots in the leading frame in the present study) or simultaneously with the mask (corresponding to the dots in the trailing frame in the present study). Congruently with the present outcome, Breitmeyer found that metacontrast masking was reduced when the additional stimuli were part of the target display but not when they were part of the masking display. Taken together, these results are strongly suggestive of a correspondence between metacontrast masking and suppression of visible persistence.

General Discussion

If the leading elements of a two-part display are embedded in a larger configuration (a grid, in this case), the SOA over which temporal integration can occur is significantly increased. By inference, this means that the visible persistence of the leading frame remains available over longer temporal intervals than would be the case without the additional contours. The added contours do not cause visible persistence to actually increase in duration; rather, they act to reduce the amount of suppression exerted by the temporally trailing stimuli.

On the basis of the present work, and on the outcome of similar work done with metacontrast paradigms (Breitmeyer, 1978; Breitmeyer et al., 1981; Stoper & Banffy, 1977; Werner, 1935), it can be stated with confidence that the additional contours serve an equivalent function in temporal-integration and in metacontrast paradigms. In both cases, the additional contours act to protect the traces of the leading stimuli by reducing or eliminating the suppressive effects of the trailing stimuli.

In conjunction with earlier findings (Di Lollo & Hogben, 1985, 1987; Farrell, 1984), the present work provides converging evidence congruent with the proposition that suppression of visible persistence and metacontrast masking belong to the same class of events.

Having examined, and guardedly accepted, the conjecture that additional contours serve equivalent functions in persistence and metacontrast, a logical next step is to identify the mechanisms by which the additional contours perform such functions. However, having considered a number of alternatives, we agree with Stoper and Banffy (1977) that this is no simple matter. Although we cannot make any firm suggestions, it may be useful to touch on some of the issues related to the search for such a mechanism.

On many instances, the display sequence seemed to suggest a link between presence of the grid lines and perception of motion—or, rather, its absence. Although coherent motion was never observed, local motion between adjacent dots was often seen in gridless displays (which were also characterized by suppression of visible persistence), but not in displays with the grid (in which suppression was much reduced or totally absent). Thus, in our displays, suppression and motion were found to covary with the presence of the grid. Were it assumed that both the perception of motion and the metacontrast-like suppression that often accompanies it depend on the same mechanisms, then the effect of the grid could plausibly be related to the functioning of those mechanisms. However, Stoper and Banffy (1977) have shown convincingly that suppression and motion cannot be based on precisely the same mechanisms. Indeed, there are good reasons for believing that the two are independent phenomena (e.g., Bridgeman, 1971; Stoper & Banffy, 1977; Weisstein & Growney, 1969).

This is not to say, however, that suppression and motion may not both depend on common, more fundamental processes, such as inhibitory interactions among successive stimuli (e.g., Breitmeyer, 1984; Matin, 1975). Were some form of inhibition at the basis of the suppressive effects in metacontrast and in visible persistence, then the grid could be viewed as interfering with the ongoing inhibitory process. Pertinent in this respect are the observations of van der Wildt and Vrolijk (1981), who described a wave of inhibition that propagates from the point of excitation and suppresses ongoing activity produced by earlier stimuli within the area of propagation. Viewed in terms of the present work, the inhibition propagating from any given dot in the trailing frame could either have a clear path to the locus of activity of a leading dot (in gridless displays), or it would have to cross the area of activity produced by the intervening grid contour. On the assumption that the strength of inhibition is somehow diminished when it encounters the area of activity produced by the grid, a lessened inhibition of the traces of the leading dots would follow. On this option, the contours of the grid intervening between dots in the leading and trailing frames would act as a protective shield against the propagating wave of inhibition. However, as has been shown by Breitmeyer (1978), by Breitmeyer et al. (1981), and by Stoper and Banffy (1977), suppression is reduced even if the additional contours are not spatially interposed between leading and trailing stimuli: Mere spatial proximity without interposition is sufficient.

Reduction of metacontrast suppression (or suppression of visible persistence) by the mere spatial proximity of additional contours (without interposition) is easily explained in terms of Breitmeyer's theory of inhibitory interactions involving transient and sustained responses to visual stimulation (e.g., Breitmeyer, 1984; Breitmeyer & Ganz, 1976). In metacontrast masking, the short-latency transient activity of the mask is held to inhibit the long-latency sustained activity of the temporally leading target. The addition of extraneous contours in appropriate spatiotemporal relation to the mask is held to lead to the converse outcome, namely, suppression of the mask's transient activity by the sustained activity generated by the additional contours in the display. This theory is supported not only by the extant psychophysical evidence but also by the outcomes of neurophysiological investigations of the inhibitory interactions among transient and sustained responses (e.g., Singer & Bedworth, 1973).

At this stage, searching for the underlying mechanisms would be made easier if more were known about the effect of the grid in a variety of temporal relations with the two frames of the matrix display. Onset and termination of the grid could be varied independently of the matrix dots, much as the timing of the additional contours was manipulated by Stoper and Banffy (1977) to study their effects on motion perception and metacontrast suppression. Whatever the strategy, the problem posed by the suppression of persistence of leading stimuli is worth studying, for it almost certainly underlies the suppression of multiple imaging and "smearing" of objects both in real and stroboscopic motion.

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