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Spatial Vision Thresholds in the Near Absence of Attention

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It is well known that attention increases the discriminability of some types of spatial information. To ascertain more specifically which types of spatial information benefit from attention, we have measured spatial vision thresholds both in the presence and in the near absence of attention. To obtain near absence of attention, we induce subjects to focus attention elsewhere in the display by means of a suitably demanding concurrent visual task. We measure contrast and orientation thresholds for sine-wave gratings, as well uni- and bidirectional offset thresholds for vernier targets. The results suggest that attention selectively lowers some thresholds but not others: orientation thresholds are far more affected than contrast thresholds, and bidirectional vernier thresholds are far more affected than unidirectional thresholds. © 1997 Elsevier Science Ltd.

Visual filters Gain Tuning Concurrent tasks

INTRODUCTION

Although it has long been recognized that visual processing is strongly influenced by attention (Helmholtz, 1850; James, 1890), the precise nature of this influence remains unclear. Most would allow that attention does more than simply select from among the visual information that is made available by early stages of visual processing and, indeed, it would seem that attention actively shapes the early visual processing of attended information to suit current behavioral requirements. In the terminology of signal-detection-theory (SDT; Green & Swets, 1966; Macmillan & Creelman, 1991), attention alters the sensitivity or d' of a visual discrimination rather than merely its criterion or β. For example, when the amount of attention paid to a particular stimulus is manipulated with visual "cueing", the d' for discriminating, say, a simple shape tends to be significantly larger at cued than at uncued locations (Bashinski & Bacharach, 1980; Shaw, 1984; Müller & Findlay, 1987; Downing, 1988; Nakayama & Mackeben, 1989). Even stronger evidence for attentional effects on d' comes from experiments in which attention is divided in various proportions between two concurrent visual tasks (Sperling & Melchner, 1978; Duncan, 1984; Braun & Sagi, 1990, 1991; Bonnel *et al.*, 1987; Bonnel & Miller, 1994; Braun, 1994; Braun & Julesz, 1997).

Neurophysiological studies confirm that attention affects almost all levels of visual processing. In the visual cortical areas of the so-called "object" pathway (areas V1, V2, V3, V4, and inferotemporal areas; Desimone & Ungerleider, 1989; Felleman & Van Essen, 1990), up to half the neurons respond more strongly to a stimulus associated with a visual task carried out by the animal than to a stimulus that is viewed passively (presumably because the task-relevant stimulus is attended; Moran & Desimone, 1985; Spitzer *et al.*, 1988; Haenny *et al.*, 1988; Chelazzi *et al.*, 1993; Motter, 1994; Maunsell, 1995). In some cases even neurons in area V1 exhibit attentional effects of this kind (Motter, 1993; Press *et al.*, 1994). Functional imaging studies leave little doubt that similar attentional effects operate in humans (Corbetta *et al.*, 1990; Maunsell, 1995).

Many psychophysical studies of attention have relied on the closely related paradigms of visual search and visual texture processing (Treisman & Gelade, 1980; Julesz, 1981, 1991; Treisman, 1991, 1992, 1993; Watt, 1991; Duncan & Humphreys, 1989, 1992; Wolfe, 1994). A somewhat different approach takes advantage of the fact that reportable visual experience does not cease in the near absence of attention. For example, sensitivity (d') for a luminance increment is rather similar at attended and unattended locations (Bashinski & Bacharach, 1980; Shaw, 1984; Müller & Findlay, 1987; Bonnel *et al.*, 1992). The same is true for sensitivity d' for a stimulus with a unique feature (i.e., shape, color, motion, etcetera) which is embedded in a sufficiently dense and uniform array of stimuli lacking this feature (Nakayama & Mackeben, 1989; Braun & Sagi, 1990, 1991; Braun, 1993, 1994). The visual response to stimuli that are "unique" in this sense is thought to be particularly strong because of pervasive lateral inhibition between similar features at nearby visual locations, which attenuates

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responses to all other stimuli in such a display (Sagi & Julesz, 1985, 1987; Koch & Ullman, 1985; Malik & Perona, 1990; Rubenstein & Sagi, 1990). Thus, lateral inhibition explains why stimuli distinguished by a unique feature are visually salient and "pop out" from the display. As this lateral inhibition operates pre-attentively and "in parallel", stimuli rendered salient by a unique feature can guide eye movements and shifts of attention (Julesz, 1981, 1991). Accordingly, it should come as no surprise that such stimuli are readily reported even when attention focuses elsewhere in the display (Braun & Sagi, 1990, 1991; Braun, 1993, 1994).

If visual information can be reported in the near absence of attention, it is of evident interest to compare psychophysical performance under this condition with performance when attention is fully availabe (Braun, 1994; Braun & Julesz, 1997). This comparison must necessarily throw light on the ways in which visual experience is altered and augmented by attention.

The present study investigates early visual processing in the near absence of attention. We chose to measure contrast thresholds as well as orientation thresholds for sinusoidal gratings, partly because these thresholds are well characterized under normal conditions when attention is fully available (Rovamo & Virsu, 1979; Virsu & Rovamo, 1979; Orban *et al.*, 1984), and partly because these thresholds reflect the spatial frequency and orientation tuning of the visual filters that characterize the first stage of visual processing (reviewed in Spillman & Werner, 1990; Regan, 1991). In addition, we studied unidirectional and bidirectional offset thresholds for vernier targets, because these thresholds may also relate to the tuning properties of visual filters (Westheimer & McKee, 1977; Wilson, 1986, 1991; Fahle, 1991; Waugh *et al.*, 1993; Harris & Fahle, 1994). By re-measuring these thresholds in the near absence of attention, we hoped to learn whether either the visual filters themselves or the interactions between visual filters are affected by attention.

To measure thresholds in the near absence of attention, we ask subjects to carry out two concurrent visual tasks, one of them designed to be highly demanding of attention ("primary task"). As a result, optimal performance on this task is reached only when attention is almost fully focused on it and thus almost completely withdrawn from the other task ("secondary task"). Performance on the primary task is monitored to ensure that subjects maintain this highly unequal division of attention. Thus, the concurrent task paradigm ensures that substantially less attention is available for the secondary task than would be available without the primary task. Of course, it does not necessarily ensure that attention is entirely withdrawn from the secondary task. For this reason we speak of the near absence, rather than the absence, of attention. Further details on the concurrent task paradigm can be found elsewhere (Braun, 1994; Braun & Julesz, 1997).

Using this approach, we have shown that the near absence of attention exacerbates visual search asymmetries (Braun, 1994). A qualitatively identical pattern of results was encountered by Schiller & Lee (1991) following a lesion in area V4. Thus, it appears that the absence of attention produces behavioral deficits that, at least in some respects, are comparable with those produced by a lesion in area V4. As mentioned, we have also shown that near absence of attention does not interfere with the detection of stimuli rendered salient by a unique feature, and that this is true even in the threshold region ($d' \sim 0.3$) (Braun, 1994; Braun & Julesz, 1997). In general, the residual visual experience in the near absence of attention seems to be considerably richer than hitherto appreciated, and permits even the discrimination of simple features of salient stimuli (Braun & Julesz, 1997).

METHODS

Stimuli were generated by a Silicon Graphics computer system and displayed on a high resolution color monitor (1000×1280 pixels). Lightness and color of each pixel were determined by 3×8 bit RGB values. The frame rate was 72 Hz. Viewing was binocular, from a distance of about 120 cm, resulting in a display of approximately 12.5×16 deg of visual angle, with 1 deg corresponded to 80 pixels. Average screen luminance was 26.6 cd/m^2. For the contrast range used in the contrast sensitivity experiment, luminance was a linear function of pixel grey level (accuracy 2%). The room luminance was about 5 cd/m^2.

Three subjects participated in the experiment. Each subject was trained and tested for more than 30 hr. They were Caltech students and received $10 per hour for participating in the experiment. Not all subjects participated in all experiments, but every condition was investigated with at least two subjects. All subjects had normal or corrected to normal vision.

We used an adaptive staircase method to measure thresholds, specifically, the up–down transformed-response (UDTR) method suggested by Levitt (1970). Changes of the stimulus were made to depend on the outcome of two preceding trials. The intensity of the stimulus (that is, luminance contrast, orientation difference, or vernier offset, depending on the experiment) was increased with each incorrect response and decreased after two successive correct responses (1-up/2-down, or 2-step). The upward and downward steps were of the same size. Levitt calculated the target probability converging to 0.707. This value is derived from the probabilities which are expected on the basis of a binomial distribution of correct and incorrect responses. Analysis of our experimental data showed that the performance at threshold is around 70% correct.

As in previous concurrent task studies (Braun, 1994; Braun & Julesz, 1997), we avoid using completely unpractised subjects since their results tend to vary greatly between individuals. For example, one subject may succeed immediately at performing two tasks concurrently while another subject may do so only after 1 or 2 days of practice. However, after two or three practice sessions (days) subjects generally converge to a

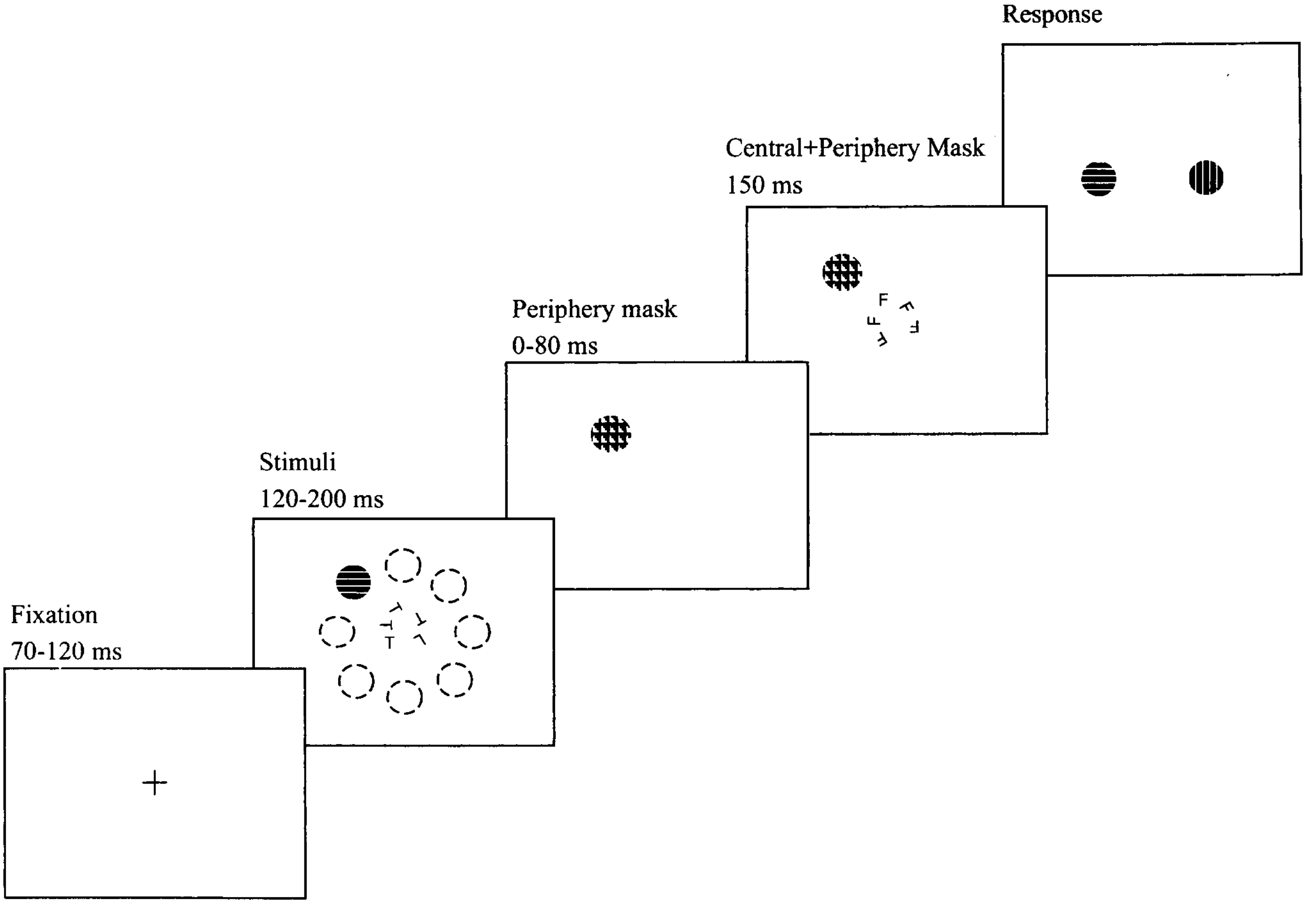

FIGURE 1. Illustration of a trial sequence. The sequence begins with a fixation display, and is continued by a stimulus display, two mask displays, and a display which prompts the observer's response. The reason for having two mask displays is that this permits the central and peripheral parts of the stimulus display to be masked independently. The central part of the stimulus display consists of five letter-shaped elements, and the peripheral part consists of either a test grating (shown schematically) or a vernier target (not shown). The peripheral test grating or vernier target appears at one of eight possible locations (shown as dashed outlines) in the stimulus display.

uniform result. A pragmatic reason for using practised subjects is our reliance on within-subject comparisons which makes it necessary to conduct tens of thousands of trials with each subject.

Although subjects were practised, performance on all tasks generally continues to improve somewhat. To ensure that all critical comparisons were based on comparable states of practice, we measured any given threshold both with and without the concurrent task during each session (day). Thus, the reported effects do not in any way reflect differences in practice level. Data were collected in blocks of 80 trials and every threshold measurement reported below was based on at least six blocks of trials. Each session consisted of alternating blocks with and without the concurrent task.

Displays always contained both central targets for the attention-demanding task (see below) and a peripheral target for the threshold measurement (sinusoidal grating or vernier target). As a result, the only difference between situations and without the concurrent task lay in the instructions provided to the subject and in the number of responses collected after each trial (Fig. 1). The central targets were the same in all experiments, while the peripheral target was different in each experiment.

Attention-demanding task

Form identification tasks in general, and letter identification tasks in particular, are thought to present a significant demand for the attentive resources of an subject (Bergen & Julesz, 1983; Kroese & Julesz, 1989; Duncan *et al.*, 1994). Here we used an identification/search task involving 5 T- or L-shaped targets with randomized positions and orientations. Maximal luminance contrast was used, and after approximately 200 msec the target elements were replaced by the elements of a perceptual mask.

The five letter targets could appear at seven possible locations: the exact center of the display and six locations at 0.9 deg eccentricity, spaced evenly around the center. On any given trial, five T- or L-shaped elements were distributed randomly among the seven possible locations, as well as rotated randomly and independently, resulting in a large number of possible configurations. There were either five Ls, five Ts, four Ts and one L, or four Ls and one T. Subjects were instructed to report whether all elements were the same (five Ts, five Ls) or whether one was different from the other four (four Ts and one L, four Ls and one T). The masking pattern for the letter task consisted of F-shaped elements. Five such elements appeared at the same locations as the five target elements of the stimulus pattern, but in different states of rotation.

We believe that the choice of this task is not critical, and that other attention-engaging tasks could have been substituted without changing the outcome. As alternatives to the present letter discrimination task, we have used RSVP tasks, color discrimination tasks, and motion discrimination tasks (unpublished results). The present task was chosen simply because its ability to engage attention is better documented than that of other tasks (Braun, 1994; Braun & Julesz, 1997). Specifically, the attention-operating characteristic (Sperling & Melchner, 1978) of two-letter discrimination tasks shows that either task engages attention *completely* (within measurement precision) (Braun & Julesz, 1997).

Threshold measurements

Contrast thresholds. We measured contrast thresholds for sine-wave gratings as a function of spatial frequency. Designating the mean luminance L and the spatial frequency f, a vertically oriented sine-wave grating of contrast C is described by the intensity distribution $I(x)$:

$$I(x) = L * [1.0 + C * \sin(f * x)]. \qquad (1)$$

To measure the contrast sensitivity function, the value of C was adjusted from trial to trial according to the staircase method discussed above.

The sine-wave grating measured 1.5 deg × 1.5 deg and at the margins of this area the luminance transition was blurred with a space constant of 0.1 deg. The grating appeared with equal probability at one of eight random locations at 4 deg of eccentricity (presentation time 200 msec, viewing distance 120 cm). Its orientation was either vertical or horizontal. Following presentation of the mask (a plaid formed by two superimposed sine-wave gratings of identical spatial frequency and orthogonal orientation), two gratings of the same size, one horizontal and one vertical, appeared at the bottom left of the display (away from all eight positions at which the grating could appear during the trial) and the subject chose one of the two by clicking the mouse on it. We measured threshold with a staircase method (see above) and this procedure was repeated for five spatial frequencies between 1 and 11.4 cycle per degree (cpd).

Orientation thresholds. To measure orientation thresholds, we presented a sine-wave grating of 4 cpd and size 1.5 deg × 1.5 deg at one of eight locations at 4 deg of eccentricity (presentation time 200 msec). The grating was either exactly vertical or slightly tilted to the left or right of vertical. The amount of tilt varied with the status of the staircase. Following presentation of the stimulus and mask, two gratings appeared at the bottom left of the display, one exactly vertical and one tilted, but otherwise identical to the grating in the stimulus. The difference in tilt reflected the status of the staircase. Subjects reported which of the two gratings had appeared in the stimulus by clicking the mouse on it. We measured thresholds for three levels of luminance contrast, 25, 50, and 100%, all three well above the threshold contrast measured in the previous experiment.

Unidirectional vernier thresholds. To measure unidirectional vernier thresholds, we presented a pair of lines (each 80 pixels or ≈1 deg in length and 1 pixel in width) forming a vernier target at one of eight possible locations at 4 deg eccentricity. Presentation time was 120 msec. The lines were tilted 20 deg from vertical, either to the left or right, in order to reduce aliasing due to finite pixel size. The lines were either precisely aligned, or exhibited a vernier offset of an amount which varied with the status of the staircase. After the stimulus and mask (lines parallel to the vernier target and spaced by 1 deg covering the entire display except the center), two pairs of lines appeared at the bottom left, one aligned and one offset, but otherwise identical to the pair in the stimulus. The difference in vernier offset reflected the status of the staircase. Subjects reported which of the two pairs had appeared in the stimulus by clicking a mouse on it.

Bidirectional vernier thresholds. To measure bidirectional vernier thresholds, we presented vernier targets which exhibited either a left or a right offset. In all other respects, they were identical to those described above. As a result, it was no longer sufficient to simply report the presence or absence of a vernier offset and observers were required to report the direction of the offset.

Experimental procedure

Subjects were instructed to fixate a cross at the center of the display before initiating each trial. The trial sequence began with a blank interval of a duration chosen randomly in the range of 70–120 msec, continued with the stimulus presentation (120–200 msec, depending on the experiment), and concluded with the mask presentation (150 msec; see Fig. 1). Central and peripheral targets were masked separately, so that different presentation times could be obtained for different parts of the display. The random duration of the blank interval at the beginning of the trial sequence prevented planned saccades (which could have defeated the masking). Although eye movements were not monitored, we are confident that the relatively short presentation time and the random location of the peripheral stimulus prevented a second fixation. Both central and peripheral masks were designed to be as effective as possible, so that relatively large differences in performance were obtained from relatively small changes in the stimulus-onset-asynchrony (SOA = interval between stimulus and mask onset). As visible persistence near contrast threshold is likely to be short (Coltheart, 1980), the necessity for masking is unclear. Accordingly, some experiments were conducted both with, and without, a peripheral mask. The central mask was always used, however.

In separate blocks of trials, subjects were asked to report on both central and peripheral targets and to ignore the central targets and report only the peripheral target. In the first case two responses were collected after each trial, in the second case only one response was required. In both cases, every mistaken response elicited immediate auditory feedback. When subjects reported on both central and peripheral targets, the two tasks were ranked, with the central task being designated primary and the second target secondary. Subjects were told that they might encounter a trade-off between central and peripheral task performance and that, in this case, they should absolutely favor the central task. A baseline performance level was established for the central task by running one or two blocks of trials in every session in which the peripheral task was ignored. When performance in the concurrent task situation fell significantly below this baseline, the block (80 trials) was rejected and the peripheral task performance was not counted towards the determination of the associated thresholds. This ensured that thresholds reflected a situation in which attention was nearly absent from the peripheral targets.

RESULTS

For the three tested subjects, average performance for the primary task alone was 87% after some practice (not shown) while the chance level is 50%. All subjects reported the primary task to be highly demanding, and that it required considerable effort and concentration. In the concurrent task situation, subjects were encouraged to maintain a comparable level of performance for the primary task. Blocks of trials with primary task performance less that 80% were rejected and the peripheral task performance in these blocks was not considered in the computation of thresholds (see Methods).

Contrast thresholds

Peripheral contrast thresholds were measured without the central task, for sine-wave gratings with spatial frequencies of 1.0, 2.0, 4.0, 8.0 and 11.4 cpd. We assumed that, in this situation, attention was fully devoted to the peripheral sine-wave grating and its discrimination. Peak sensitivity was observed at 2–4 cpd and declined towards higher spatial frequencies, consistent with previous studies (Rovamo & Virsu, 1979; Virsu & Rovamo, 1979).

With the same subjects (and in the same sessions, see Methods), we measured peripheral contrast sensitivity while the primary task was being carried out concurrently. We assumed that, in this situation, attention was almost fully devoted to the primary task and, thus, almost completely absent from the sine-wave grating and its discrimination. Contrast sensitivity obtained with and without the primary task was comparable for all subjects at all spatial frequencies. Although thresholds were consistently somewhat higher with the concurrent task, the difference does not reach significance for any subject or spatial frequency (t-test, $P > 0.05$). This was true both when the peripheral sine-wave grating was left unmasked [three subjects, Fig. 2(a)] and when it was masked [two subjects, Fig. 2(b)]. There was no significant effect of masking. A 2 (with or without primary task) ×3 (subjects) ×5 (spatial frequencies) analysis of variance was carried out for the results obtained with masking. Combining data from all spatial frequencies for each subject, performance of the primary task had a significant effect in two of three subjects ($F(1,4) = 15.20, 25.56$; $P < 0.01$; $F(1,4) = 2.25$, $P = 0.21$). Combining data for all subjects, the effect of the primary task was not significant ($F(1,20) = 0.53$; $P = 0.47$), probably due to the large performance differences between subjects.

Orientation thresholds

After finding that near absence of attention has little or no effect on contrast sensitivity, we asked how absence of attention would affect another important aspect of spatial vision-orientation discrimination. To investigate this question, we used sine-wave gratings of 4 cpd, as gratings of this spatial frequency exhibited the highest contrast sensitivity in the previous experiment. The threshold for orientation discrimination was measured in terms of the difference in orientation between vertically and off-vertically oriented gratings. This threshold was established for gratings with a luminance contrast of 25, 50 and 100%. These contrast thresholds are approximately 14, 28 and 56-times the threshold contrast determined in the previous experiment.

Thresholds were determined both with and without the primary task, that is, both in the near absence and in the full presence of attention. Figure 3(a) shows the results of three subjects on displays in which the peripheral grating was not masked. Figure 3(b) shows results of two subjects when the peripheral grating was masked by a plaid formed by superimposing two gratings of different orientation. The overall effect of a peripheral mask is not significant. Otherwise, the results with and without the peripheral mask are very similar, in that thresholds for orientation discrimination are elevated 2.9 to 5.0-fold in the near absence of attention. Specifically, thresholds are between 1 and 2 deg in the presence of attention and there is no discernible dependence on contrast level, as has been shown by previous studies (Orban *et al.*, 1984). In the absence of attention, thresholds increase to between 4 and 6 deg. This difference is significant for each subject and contrast level (t-test, $P < 0.01$).

Uni- and bidirectional vernier thresholds

With three subjects, we determined unidirectional vernier thresholds (thresholds for discriminating the presence or absence on a vernier offset) in both the presence and near absence of attention. The vernier target was always masked, and results are shown in Fig. 4. In the presence of attention, thresholds were in the range of 2.5′ to 3.5′. This would seem to be roughly consistent with threshold values of approx. 1′ reported for considerably brighter targets (960 cd/m^2) that are presented without positional uncertainty (Levi *et al.*, 1985). In the near absence of attention, thresholds were elevated slightly, by a factor ranging between 1.10 and 1.20. Although this threshold elevation was not significant for any individual subject (t-test, $P < 0.01$), a 2 (with and without primary task) ×3 (subjects) analysis of variance showed that it did reach significance when data from all subjects were combined ($F(1,2) = 149.50$; $P < 0.01$).

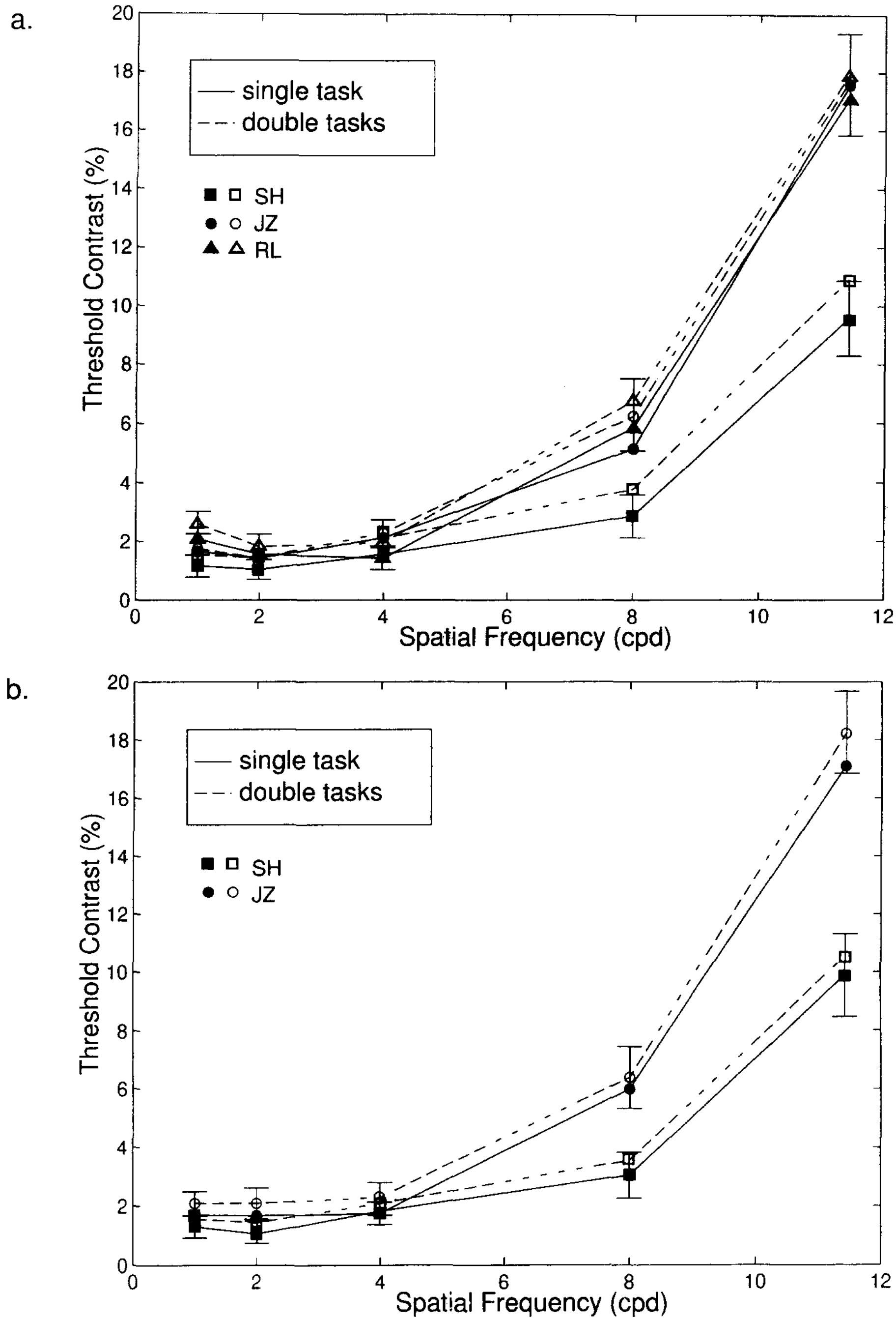

FIGURE 2. Contrast thresholds in the full presence and near absence of attention. Threshold contrast is plotted as a function of spatial frequency of the test grating. Thresholds obtained when attention is fully available ("single task") are plotted with solid symbols and solid lines. Thresholds obtained when attention is nearly absent ("double task") are plotted with open symbols and dashed lines. (a) Contrast thresholds without peripheral masking (three observers); (b) contrast thresholds with peripheral masking (two observers). Error bars represent the average standard error at each spatial frequency and were computed separately for single and double tasks.

With the same three subjects we determined bi-directional vernier thresholds (thresholds for discriminating left or right vernier offsets) in both the presence and near absence of attention. Again the vernier target was masked. As shown in Fig. 4, thresholds in the presence of attention were in the range of 3.0′ to 4.0′ and thus somewhat larger than the unidirectional thresholds. This difference is consistent with reports that extrafoveal vision poorly discriminates spatial phase (Rentschler & Treutwein, 1985). In the near absence of attention, thresholds were elevated by a factor ranging from 1.80 to 1.90 across observers. This difference was significant for each observer (t-test, $P < 0.01$). This shows that near absence of attention has a markedly different effect on bi-directional than on unidirectional vernier thresholds.

DISCUSSION

We have measured a number of spatial vision

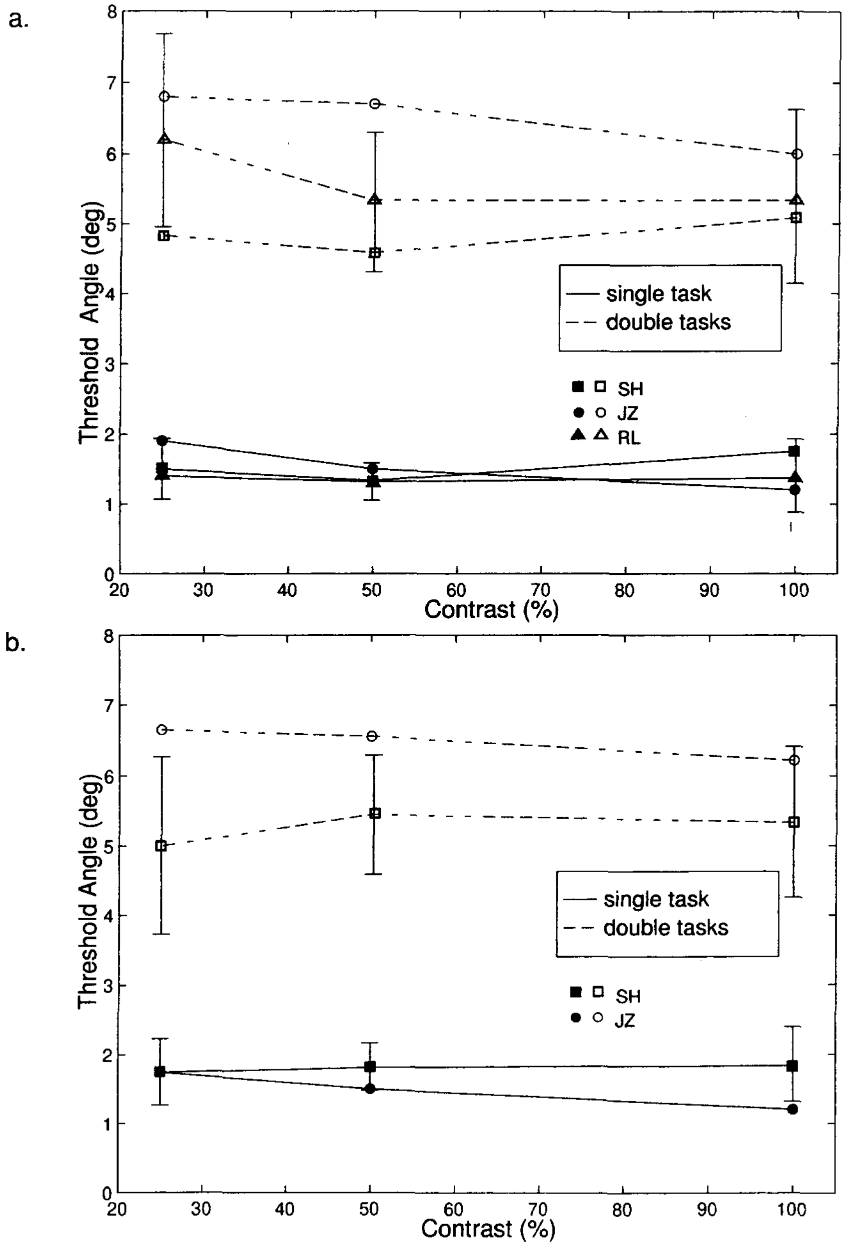

FIGURE 3. Orientation thresholds in the full presence and near absence of attention. Threshold orientation is plotted as a function of luminance contrast of the test grating. Thresholds obtained when attention is fully available ("single task") are plotted with solid symbols and solid lines. Thresholds obtained when attention is nearly absent ("double task") are plotted with open symbols and dashed lines. (a) Orientation thresholds without peripheral masking (three observers); (b) orientation thresholds with a peripheral mask (two observers). Error bars represent the average standard error at each luminance contrast and were computed separately for single and double tasks.

thresholds in both the full presence and near absence of attention. We find that thresholds can be established with traditional staircase methods in both situations. This is consistent with our previous finding that residual visual experience in the near absence of attention is considerably richer than hitherto appreciated and can be readily studied with appropriate psychophysical paradigms (Braun & Sagi, 1990, 1991; Braun, 1994; Braun & Julesz, 1997).

The most interesting aspect of the present results is that the thresholds investigated differ substantially in the degree to which they depend on attention. For example, near absence of attention has, at most, a small effect on contrast thresholds for sine-wave gratings and on unidirectional vernier thresholds but a rather large effect on orientation thresholds for sine-wave gratings and bidirectional vernier thresholds.

Note that the observed small effect of attention on contrast and unidirectional vernier thresholds may actually be an overestimate of the true effect. When two tasks are performed concurrently, as was the case in the present experiments, one may expect some interference at post-perceptual levels of processing (i.e., response encoding and execution). Such post-perceptual interference would compound any perceptual (i.e., attentional) interference (Allport, 1980; Duncan, 1980;

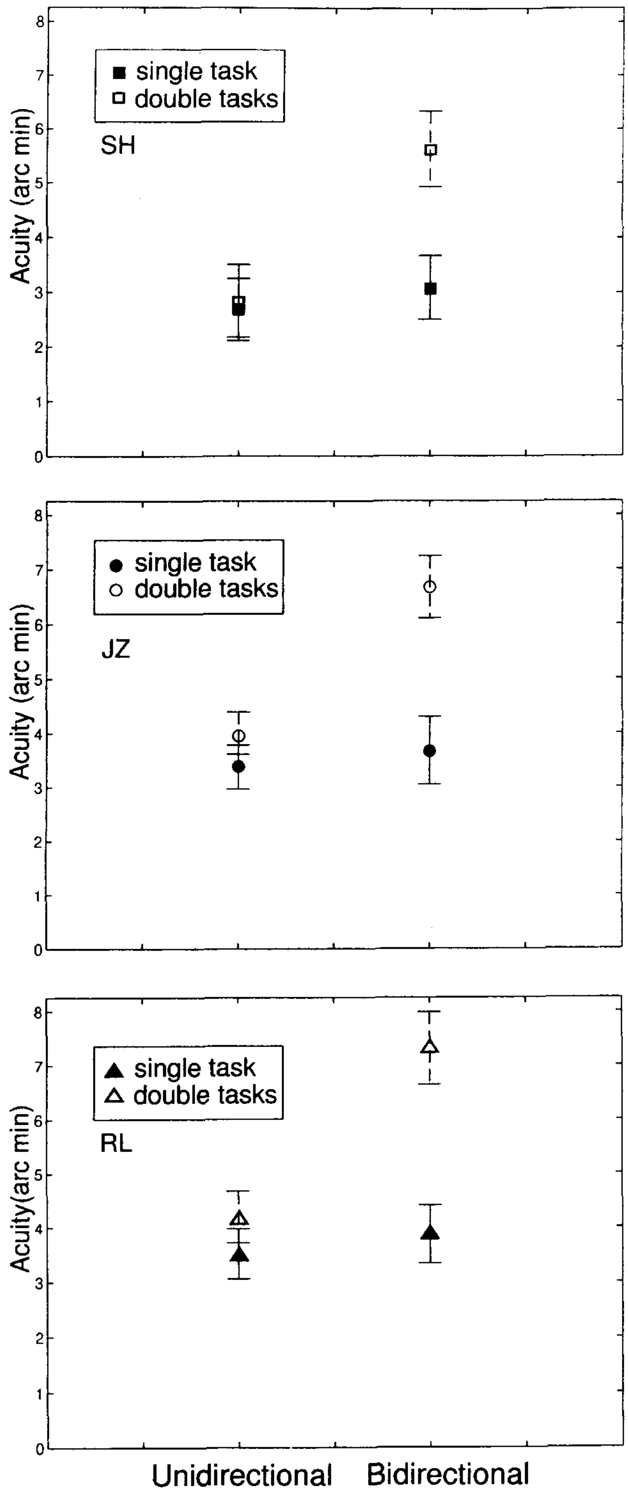

FIGURE 4. Uni- and bidirectional vernier thresholds in the full presence and near absence of attention. Threshold vernier offset is plotted for unidirectional vernier discrimination (observers report "offset" or "no offset") and for bidirectional vernier discrimination (observers report "left offset" or "right offset"). Thresholds with attention fully available ("single task") are plotted with solid symbolds and thresholds with attention nearly absent ("double task") are plotted with open symbols. (a)–(c) Data for three observers.

Pashler, 1991). Accordingly, the small elevation of orientation and bidirectional vernier thresholds by the concurrent task may well have been due to post-perceptual rather than perceptual interference.

What could account for the differential dependence on attention of the investigated spatial vision thresholds? The conventional view is that "discrimination" judgments depend on attention to a greater extent than "detection" judgments (e.g., Bashinski & Bacharach, 1980; Shaw, 1984; Müller & Findlay, 1987; Downing, 1988; Bonnel & Miller, 1994; Bonnel *et al.*, 1992). The intuition behind this distinction is that the perceptual distinction between larger or smaller sensory signals ("detection") poses a much simpler problem for the visual system than the distinction between sensory signals that are equally large but differ in qualitative ways ("discriminination").

Indeed, our results on sine-wave gratings can be understood in terms of this distinction. Contrast sensitivity, which exhibits little or no dependence on attention, almost certainly represents a "detection" threshold. Even though observers reported grating orientation (vertical or horizontal), the most demanding aspect of the task was probably not the discrimination of its orientation but the detection of the grating at its varying peripheral location. Thus, performance was determined primarily by the ability to distinguish between larger and smaller sensory signals (grating location and empty locations, respectively). On the other hand, the visual differentiation of grating orientation (vertical or tilted), which exhibits a pronounced dependence on attention, is almost certainly a "discrimination": assuming that gratings of all orientations elicit a response of comparable size, this differentiation concerns responses that differ qualitatively rather than quantitatively.

A similar account can be given for our results on vernier targets, provided we make certain assumptions about the mechanisms that underlie vernier acuity judgments (Wilson, 1991; Harris & Fahle, 1994). It is thought that certain visual filters exhibit spatial response properties that can be loosely described as "end-stopped", and that these filters detect stimulus configurations such as the abrupt line termination in a vernier target (Rosenthaler *et al.*, 1992; Heitger *et al.*, 1992). End-stopped filters would signal the presence, but not the direction, of a vernier offset and could therefore mediate unidirectional but not bidirectional vernier discrimination. Because end-stopped filters would operate in parallel across the field of view, vernier discrimination is especially likely to be based on such filters when there is spatial uncertainty about the position and orientation of the target (as in our case). In other situations, for example when the position and orientation of the vernier target is known, other mechanisms seem to come into play (Wilson, 1991; Waugh *et al.*, 1993; Harris & Fahle, 1994; see below).

If it is true that unidirectional vernier thresholds reflect the differential response of end-stopped filters to targets with and without an offset, then this differentiation would represent a "detection". This would account for the fact that reduced attention leaves undirectional thresholds almost unchanged and that visual search for a target with offset is independent of the number of targets in the display ("parallel search", Fahle, 1991; see also Wolfe *et al.*, 1992). Bidirectional vernier thresholds, however, would have to be based on the responses of additional mechanisms, and would, thus, represent a^discrimination". This would account for the fact that reduced attention raises bidirectional thresholds, and that visual search for an offset in a particular direction requires more time when there are more targets in the display ("serial search"; Fahle, 1991).

Although these considerations show that the observed attentional demands are consistent with a detection/discrimination account, they also expose the essential weakness of this account: the detection/discrimination distinction depends on which mechanisms are presumed to underlie visual performance and, since these are generally unknown, is of limited predictive value. For example, it has also been proposed that vernier offset judgments are based on visual filters sensitive to a range of orientations, especially orientations at 15 deg to either side of the axis of the vernier target (Wilson, 1986, 1991; Waugh *et al.*, 1993). If this was the case, then left offset, no offset, and right offset elicit visual responses of comparable strength and any differentiation between these alternatives would be a "discrimination". Indeed, there is evidence that a mechanism of this type is sometimes used: in some situations, left and right offset are approximately twice as discriminable than presence or absence of offset (Harris & Fahle, 1994). This illustrates how ignorance of the mechanisms that underlie a visual judgment blurs the detection/discrimination distinction, even in exhaustively researched instances such as vernier offset judgments.

The deeper question would seem to be in what way attention alters the distribution of responses across visual filters. Does attention selectively enhance or attenuate the responses of individual filters? Or does attention simply strengthen or weaken certain interactions between filters, for example, the inhibitory interactions between filters at the same visual location suggested by Heeger and others (Heeger, 1993; Carandini & Heeger, 1994), or the competitive interactions between filters at distant visual locations postulated by Koch, Desimone and others (Koch & Ullman, 1985; Desimone & Duncan, 1995)? Or perhaps attention simply attenuates responses outside an attended area that is defined in anatomical terms, for example, the area covered by the receptive fields of a certain number of hypercolumns (Hubel & Wiesel, 1977)?

Invasive studies of non-human primates would seem to have contributed relatively little to the resolution of these issues. In visual cortical areas V2 and V4, it has been reported that attention sharpens orientation tuning of neurons (Spitzer *et al.*, 1988), that orientation tuning remains unchanged but response levels increase (McAdams & Maunsell, 1996), and that response levels remain roughly the same for attended stimuli but decline for unattended stimuli (Moran & Desimone, 1985; Reynolds *et al.*, 1994). In visual cortical area V1, where receptive field properties correspond most closely to psychophysically defined visual spatial filters, attentional effects are rather difficult to observe but are consistent with a suppression of responses to unattended stimuli (Motter, 1993; Press *et al.*, 1994).

Thus, it would appear that appropriately designed psychophysical paradigms remain the most promising approach to understanding attention and its effect on early levels of visual processing.

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