

SUSTAINED AND TRANSIENT COMPONENTS OF FOCAL VISUAL ATTENTION

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Abstract—Human observers fixated the center of a search array and were required to discriminate the color of an odd target if it was present. The array consisted of horizontal or vertical black or white bars. In the simple case, only orientation was necessary to define the odd target, whereas in the conjunctive case, both orientation and color were necessary. A cue located at the critical target position was either visible all the time (sustained cuing) or it appeared at a short variable delay before the array presentation (transient cuing). Sustained visual cuing enhanced perception greatly in the conjunctive, but not in the simple condition. Perception of the odd target in the conjunctive display was improved even further by transient cuing, and peak discrimination performance occurred if the cue preceded the target array by 70–150 msec. Longer delays led to a marked downturn in performance. Control experiments indicated that this transient attentional component was independent of the observers' prior knowledge of target position and was not subject to voluntary control. We provide evidence to suggest that the transient component does not originate at the earliest stages of visual processing, since it could not be extended in duration by flickering the cue, nor did it require a local sensory transient to trigger its onset. Neither the variation in retinal eccentricity nor changing the paradigm to a vernier acuity task altered the basic pattern of results. Our findings indicate the existence of a sustained and a transient component of attention, and we hypothesize that of the two, the transient component is operative at an earlier stage of visual cortical processing.

Focal attention Visual search Pattern recognition Vernier acuity

INTRODUCTION

Recent neurophysiological work in alert primates indicates that the response properties of single cells in various cortical areas depend on task-related demands and the animal's attention. For example, cells in areas V4 and IT show a different response depending on whether the animal is required to pay attention to a particular region of the visual field (Richmond, Wurtz & Sato, 1983; Moran & Desimone, 1985). The receptive fields in area V4 are larger than those in area V1 and were shown to shrink down to a very small region, coincident with the locus in the visual field where the monkey had to make a visual discrimination (Moran & Desimone, 1985). Other studies in primates have demonstrated that neurons in the parietal cortex and thalamus are also influenced by the attentive state of the monkey (Bushnell, Goldberg & Robinson, 1981; Petersen, Robinson & Morris, 1987). Little or no such effects, however, are seen in striate cortex (Wurtz, Goldberg & Robinson, 1980; Moran & Desimone, 1985).

These neurophysiological results parallel the fact that human observers can direct their visual attention to particular regions of the visual field without foveation. As is often the case with significant visual phenomena, Helmholtz (1896) made some of the primary observations:

“The electrical discharge illuminated the printed page for a brief moment during which the image of the sheet became visible and persisted as a positive afterimage for a short while. Hence, perception of the image was limited to the duration of the after-image. Eye movements of measurable size could not be performed during the duration of the flash and even those performed during the short persistence of the after-image could not shift its location on the retina. Nonetheless, I found myself able to choose in advance which part of the dark field off to the side of the constantly fixated pinhole I wanted to perceive by indirect vision. Consequently, during the electrical illumination, I in fact perceived several groups of letters in that region of the field . . . The letters in most of the remaining part of the field, however, had not

reached perception, not even those that were close to the point of fixation.”*

Helmholtz's phenomenological observation indicated the existence of a mechanism which can move attention independent of eye movements. Surprisingly, early results in the modern era of experimental psychology failed to find much objective evidence for the existence of spatially directed attention (Mowrer, 1941; Mertens, 1956; Grindley & Townsend, 1968) and it has been only relatively recently that one can say that objectively valid performance measures of selective visual attention existed (Eriksen & Hoffman, 1972; Bashinski & Bacharach, 1980; Posner, Snyder & Davidson, 1980; Remington & Pierce, 1984). Human electrophysiological studies using evoked potentials also show evidence for spatially directed attention (Van Voorhis & Hillyard, 1977).

Most recently, the concept of visual attention has been employed as an explanatory principle to interpret a range of new visual phenomena. In particular, work on texture segregation as well as experiments on visual search (Treisman & Gelade, 1980; Bergen & Julesz, 1983; Julesz & Bergen, 1983) used the notion of a mobile attentional "window". Our interest in the subject stems from observations on visual search where we concluded that human subjects could direct attention to a particular stereoscopic depth plane. To account for our findings on visual search (Nakayama & Silverman, 1986a, b), we have developed a speculative framework outlining the relation between early visual processing and visual memory (Nakayama, 1989). This formulation draws on earlier concepts regarding the nature of pre-attentive vision, most notably those outlined by Neisser (1967) and later by Julesz (1984). Julesz in particular has consistently emphasized the distinction between pre-attentive vision and "higher" vision by arguing that the processing rules in pre-attentive vision are simpler and distinct from higher-order processes. Most notable is his notion of the primitive nature of form recognition in early vision, confined to measuring local density or density gradients of

elementary features called "textons" (Julesz & Bergen, 1983). An important function of this pre-attentive system is to assist in directing the "attentive" visual system to regions with feature or texton gradients to employ more sophisticated mechanisms of form processing (see Koch & Ullman, 1985). In this paper, we report studies where an observer is asked to direct attention to particular loci in an array containing many targets, and we have measured discriminative performance under a variety of conditions.

The results suggest the existence of two distinct attentional processes, a sustained and a transient component. We first describe conditions where the sustained component is operative, followed by a section outlining the characteristics of the transient component.

SECTION I: SUSTAINED VISUAL ATTENTION

Methods

While maintaining center fixation, the observers searched for an odd target in a 64 element display of 10×9 ($H \times V$) containing white and black vertical and horizontal bars (30×15 min arc) on a gray background. Two types of arrays corresponding to simple and conjunctive feature configurations (Treisman & Gelade, 1980) were used and they are schematized in Fig. 1. Rather than using a reaction time paradigm, however, we used a technique similar to that employed by Bergen and Julesz (1983). We presented a search array (either containing the odd target or not) for a variable duration, followed by a masking stimulus of 250 msec duration containing white and black squares of different sizes (see upper right panel in Fig. 6). The task of the observer was to determine if an odd target was present and if so, to report its type. The targets and the observer's choice of responses are schematized in Fig. 2. Cuing in these experiments was sustained because a visible cue was on all the time and its position did not vary from trial to trial. Viewing distance was 71 cm and viewing was binocular.

In the simple search case the odd targets differed from the distractors in orientation (as in Fig. 1). All the distractors were oriented vertically (and randomly colored either black or white), while the odd target was horizontal and could be of either color. Thus, three different stimulus presentations could occur with equal

*This paragraph was translated by one of the authors (MM), because we were unable to find it in English. J. P. C. Southall based his translation on the 3rd German edition (1909), which in turn is based on the original (first) edition (see the preface by W. Nagel to the 3rd edition). It appears as if Helmholtz added this observation to the second edition.

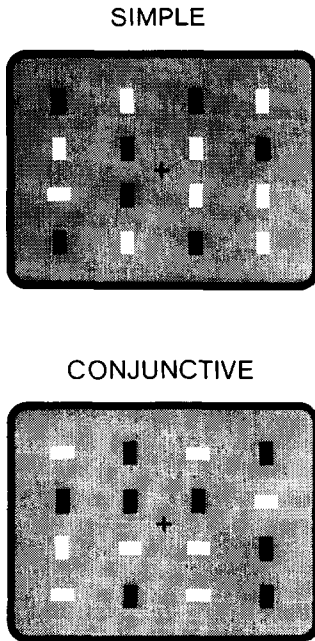


Fig. 1. Portion of the 8 × 8 search arrays used in experiment 1 and 2 (reduced to 4 × 4 elements for clarity): simple—the odd target (horizontal) differs from the distractors only in orientation. Conjunctive—the odd target differs from the distractors in orientation and color.

probability. The observer had to make a forced choice response noting either the presence of a white odd target, a black odd target, or no odd target at all.

In the conjunctive search case, the definition of the odd targets was more complex, differing in two feature dimensions (see Fig. 1). Thus, the distractors consisted of a set of horizontal white bars intermingled randomly with vertical black bars. Odd targets were the ones that broke this pattern: either a vertical white bar or a horizontal black bar. Again, a 3-alternative forced-choice condition was employed, requiring the observer to distinguish between the equally probable white or black odd targets, or the presentation of no odd target at all.

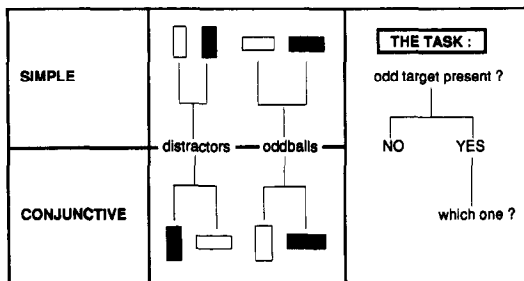


Fig. 2 Targets, distractors, and the observers task in the simple and conjunctive condition.

The targets were presented on a CRT screen, driven by a micro-computer (Commodore 64 or Amiga 1000). The frame rate was 60 Hz (non-interlaced) and the luminance of the gray background was in the photopic range (150 cd/m²). The observers were provided with a fixation mark and unless noted were asked to maintain fixation there.

Although we were confident that our trained observers were able to maintain proper fixation, we monitored eye movements during the collection of critical sets of data, where involuntary lapses of fixation could jeopardize the validity of the results. For this purpose we used a differential infra-red reflection monitor (Brown, Adams, Jampolsky & Muegge, 1977) capable of measuring horizontal eye movements with an accuracy of 4 min arc. Its output was digitized at 60 Hz and monitored on-line by the computer running the experiment. A calibration routine requiring that the observer make repeated fixations on 3 standard targets preceded every block of 20 trials. Our computerized procedure was designed to reject responses that were preceded or accompanied by eye movements greater than 24 min arc in either horizontal direction. Note that this constitutes approximately half the distance to the target nearest to the fixation mark for Expts 1 and 2 and even a smaller proportion for some of the other experiments. Auditory feedback informed the observer when a trial had been rejected. A bite bar was used to stabilize head position.

Although not specifically designed to monitor vertical eye movements, our system was also quite sensitive to the lid movements normally associated with them. It was empirically determined that a pure vertical eye movement of 45 min arc could trigger the computer's trial rejection routine. Thus, the system could assure fixation within an elliptical window of approx. 50 × 90 min arc (H × V).

We used 7 subjects, 17–47 years of age with varying degrees of experience in visual perception and performance tasks. Not all of them did all the experiments reported here. We will indicate the number of subjects used in the description of each experiment. All subjects, however, had at least 4 hr of practice comprising 3000 trials before the commencement of data collection and most had much more practice than this. Two of the subjects (MC and JD) never received explanations regarding the purpose of the experiment. All data points in the graphs represent the percentage of correct responses in

100 trials collected in interleaved blocks, each containing 20 trials*.

Results

Experiment 1: cuing enhances the discrimination of targets in a conjunctive but not in a simple search display

First we report experiments where there was no cue and the observers had no prior knowledge as to the locus of the target. The search array was presented for a variable duration followed by the mask. The performance of two subjects was measured as a function of stimulus duration and the results for the simple and conjunctive display can be seen as open symbols in Fig. 4. The simple search results are seen on the left, the conjunctive results on the right. Most obvious is the large difference in performance in the two situations. While performance rises very rapidly in the simple condition and becomes essentially perfect at durations of about 100 msec, it behaves differently in the conjunctive case. Here, performance rises slowly and does not reach even a 90% correct level until a duration of 1500 msec, more than 10 times the time required to get a comparable performance in the simple "odd orientation" paradigm. This result indicates that the conjunctive search task for "orientation and color" is indeed much more difficult, and is consistent with earlier reports that such conjunctive displays generally require a serial search (Treisman & Gelade, 1980; Nakayama & Silverman, 1986; Nakayama, 1989). By implication, such an interpretation assumes that all the targets have comparable visibility in each situation and that the large differences in perception between the two cases is the result of selective processing at a particular locus in the visual field.

To show that this is the case, we presented a 1.5° red outline square denoting the critical location. Thus, rather than mentally scanning the entire display to find the anomalous target, the observer needed to pay attention only to the interior of the red square. For observer MM,

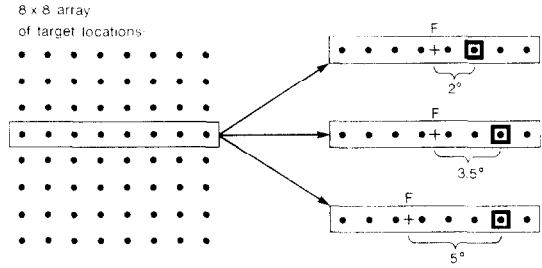


Fig. 3. Schematic representation of 8 × 8 target and distractor array showing the possible sites where the cue could appear for the sustained and some of the transient experiments. With the exception of the 5° eccentricity case, a fixation mark was placed in the center of the 4th row of stimulus elements. In the 5° case it was moved to the left by one inter-element spacing. The full size of the array subtended 10(H) × 9(V)°.

the position of the red square always was on the 4th row of elements of the 8 × 8 display but its distance from the fixation mark varied from session to session (2.0, 3.5 or 5.0°, see Fig. 3). For observer NW, only one position was studied (3.5° to the right of fixation).

The performance under these conditions can be seen as the filled symbols in Fig. 4. For

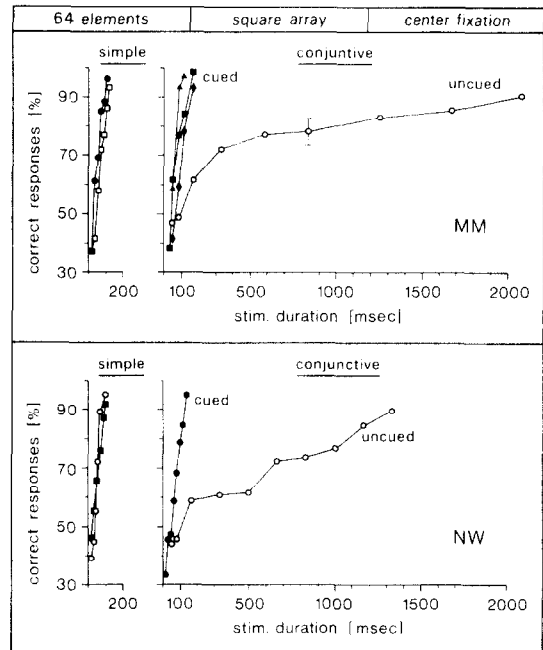


Fig. 4. Studies on sustained visual attention. Performance plotted as a function of stimulus duration for simple and conjunctive search arrays, either for the case where no cue was present and the target could appear at any of the 64 loci (open symbols) or where a cue permanently marked the target location (solid symbols). In observer MM, three eccentricities of that cued location were used: 2° (triangles), 3.5° (squares) and 5° (diamonds). For NW (lower graph), it appeared at the 3.5° position.

*Because the data are in the form of percent scores, error bars can be calculated from the standard error of a proportion $\sqrt{P \times q/N}$ (Hayes, 1973). Since $N = 100$, it should be clear that the error bars will range from a low of $\pm 2\%$ to a high of $\pm 5\%$, depending on the score. To preserve the clarity of the graphical presentation and to avoid redundancy, we have omitted the presentation of error bars for all but a few representative points.

the simple case, the performance is virtually unaffected and the presence of the cue has very little influence. It is dramatically different, however, for the conjunctive case. Here the difference between the cued and uncued case is large, with obvious improvement of performance for all but the shortest durations. Note that there is essentially no difference in performance for the different eccentricities for observer MM. This indicates that despite substantial differences in visual acuity and contrast sensitivity at the various retinal locations (Anstis, 1974; Virsu & Rovamo, 1979), it is attention rather than eccentricity which limits performance in our task. To make sure that the observer did indeed keep his fixation constant and that he was not making saccades towards the cue, we also conducted the conjunctive search experiment with the eye movement monitoring system (see open and closed triangles in Fig. 5). Note the similarity with the data shown in Fig. 4, which indicates that eye movements are not responsible for the enhanced performance seen when a cue is present. This validated the assumption that our trained observers indeed maintained their fixation as instructed.

In addition, we also ran one session where we allowed the observer to let his fixation wander anywhere on the display and the data are denoted by the open squares in Fig. 5. Surprisingly, a slight improvement of performance could only be seen at durations exceeding

600 msec, which supports the view that there is no special advantage to be gained by foveation in our task and that attention can be directed to the various peripheral loci in the display with essentially equal ease.

Experiment 2: observers can attend to a blank region without a cue

The results reported so far prompted us to ask whether the cuing stimulus itself was really necessary. Is it possible, for example, to direct one's attention to a "blank" region at a specific peripheral location before the array is presented without making eye movements while obtaining the same enhancement in perception? This is very similar to the observation originally reported by Helmholtz (1896, see above). To answer the question, we ran three observers using the conjunctive paradigm. The experiment was the same as the cuing experiment described above, except that the cue was absent. The observer was simply told that the target would appear at exactly the same locus in all trials. The observer had the task of maintaining central fixation yet directing his or her attention to a blank unmarked region of the visual field and waiting for the target array to appear. Paying attention to this peripheral "blank" locus was not easy, requiring considerable concentration. One observer (NW) found the task too demanding and could not participate in the experiment. The two other subjects found they could do the task and their measured performance was comparable to the case where a cue was present.

The functions defined by the open symbols in Fig. 5 indicate that performance rises steeply as duration is increased when the target position is known and constant, whereas the functions defined by the closed symbols indicate that it rises only slowly if it is unknown and variable. It should be noted that the data in Fig. 5 for MM were collected under our eye movement monitoring procedure described above, so we are confident that the improvement in performance cannot be attributed to lapses in eye fixation.

Discussion of Experiments 1 and 2

In the experiments described above, we presented the observer with two discrimination tasks in a 64 element search array. In the simple case, the observer had to report whether an odd target (defined by orientation alone) was present and, if so, to report its color. In the conjunctive case he had to report whether an odd target

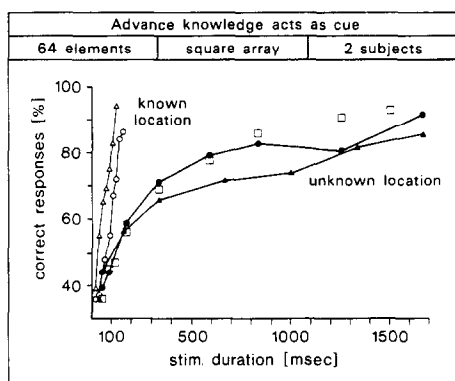


Fig. 5. Effect of prior knowledge of target position without a visible cue. The target always appeared at the same 3.5° location but was not marked by a visible cue (open triangles: MM, open circles: JD). The solid symbols (triangles: MM, circles: JD) show data from the same subjects, where target location was not known in advance but varied randomly from trial to trial and there was no cue. The unconnected open squares represent data collected while subject MM was allowed to scan the array freely and there was no cue. All data from observer MM shown in this figure were collected during eye movement monitoring (see text).

(defined by orientation and color) was present and to report its color. We found that the experimental manipulation of selective attention could improve performance only in the conjunctive paradigm.

Shaw (1984) suggested that attention can only be demonstrated for discrimination and not for detection experiments. In Shaw's analysis, detection was equivalent to the detection of a light flash and discrimination involved a more complex digit distinction. In our case, both tasks are discrimination tasks, yet because of the ease with which targets can be discerned in the simple case, cue or no cue, it behaves more similarly to Shaw's detection task.

Rather than emphasizing the distinction between detection and discrimination, we think that our results as well as Shaw's can be reasonably well accounted for by appealing to a feature differencing concept (Julesz, 1984; Koch & Ullman, 1985; Nakayama, 1989) or, more precisely, to a similarity vetoing mechanism which inhibits the responses to features which are presented more than once in an extended portion of the visual field. Here, a simple feature presented alone in a field elicits a response, but two such identical features in a field do not. The basic property of such a hypothetical neural mechanism would be to abolish the response to a feature presented to a cell's receptive field center if the same feature is present anywhere in the surround. For example, Frost, Scilley, and Wong (1981) have shown that the response of a cell responding to movement of a small spot in the receptive field center can be vetoed when another spot is moving in the same direction in a very large surrounding field (see also Frost & Nakayama, 1983). The existence of such mechanisms means that a single odd target location can be "marked" in the simple case; whereas, no site will be marked in the conjunctive case. Similar vetoing mechanisms have been observed for motion in area MT (Allman, Miezin & McGuinness, 1985), and for orientation in area 18 of the cat (Blakemore & Tobin, 1972). It is hypothesized that such a mechanism will enable a unique feature in an array to have salience by providing a single odd target with its own "cuing" signal.

In summary, our findings with sustained cuing clarify the issue as to why, under some experimental circumstances, focal attention is easily seen, whereas in others it is not. Attentional differences will be evident only in stimulus displays where attention is not automatically

and uniquely drawn to the target. As such, an added cue will do little to increase performance when a single transient stimulus appears in an otherwise blank field (Shaw, 1984; Posner & Cohen, 1984). Nor does a cue help in our "simple" case (left side of Fig. 4) because the target by itself can be singled out and marked by the pre-attentive system; the addition of a cue can add little to target visibility. It is only when the target does not act as its own cue, as in the conjunctive case, that the cue can be of benefit. Similar conclusions can be drawn from the experimental findings of Bergen and Julesz (1984) where they compared visual search performance for targets differing from distractors with various differences in line orientation.

SECTION II: TRANSIENTLY SUMMONED ATTENTION

So far we have presented evidence that attention can be focused on a given region of the visual field if the observer has knowledge as to where the target will appear. In this section, we modify our experimental paradigm to investigate the temporal aspect of summoned attention, asking how long it takes for attention to be drawn to any particular site if a cue is presented there.

Methods

The basic experiment is very similar to those described in Expts 1 and 2 except that instead of the cue remaining on for long periods of time during the intertrial interval, it is present just transiently before and during the trial. The paradigm is summarized schematically in Fig. 6 showing the sequence of visual "frames." The observer is presented with a fixation mark, then a cue appears, and after a defined interval (designated as the "cue lead time") the target appears for a given duration, and finally, this is followed by the mask (250 msec duration). Note that the cue always remains on during the presentation of the stimulus array. As attentional effects could only be seen using the conjunctive display (as shown in Fig. 1), this was employed in all remaining studies to be described (with the exception of experiment No. 9).

Initially all subjects had considerable difficulty performing in the task using the stimulus durations shown in the graphs below. Consequently, practice was conducted by lengthening the stimulus durations in the early stages and

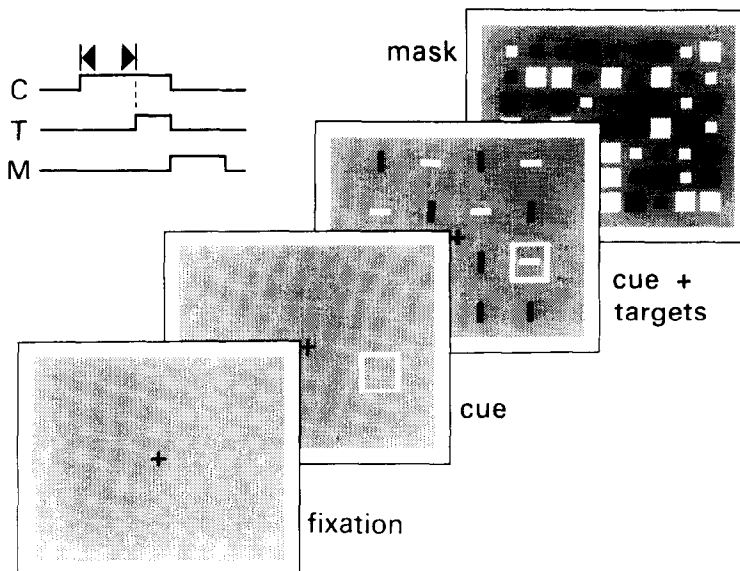


Fig. 6. Sequence of events used to study transient focal attention (Expt 3). First the subject fixated a permanently visible cross on the gray screen. Next, a red square cued the critical location. After a variable interval called the "cue lead time", the targets and the cue appeared, and this was followed by the mask, which was visible for 250 msec. The time line diagram in the upper left corner depicts the same sequence.

then gradually shortening them so that at zero cue lead time performance was essentially at chance level. Improvements in performance varied between individuals and could occur over several thousands of trials. With the exception of the data shown for MM in Fig. 7, all results were obtained after reaching this stabilization phase.

Results

Experiment 3: a transient component of attention

We started by varying cue lead time and measured performance curves for 3 different stimulus durations (see Fig. 7). The stimulus array consisted of the same 64 elements employed in Expts 1 and 2. In this experiment, the cue could be presented at any of the 64 locations, which varied from trial to trial. The cue lead time is plotted on the abscissa and the different curves represent the percentage of correct responses at stimulus durations of 33, 83 and 117 msec. The overall level of performance is better for long stimulus durations than for short ones, clearly the 117 msec performance curve is best and the 33 msec curve is worst. This relationship is not surprising and is consistent with the earlier data shown in Fig. 4 which indicated that performance improves rapidly with increasing stimulus duration. Important to note, however, is the general course of each time function. It shows that performance varies dramatically depending on the cue lead time. The common feature of all three functions is the monotonic rise in performance during the first 50 msec. This consistent rise indicates that the summoning of attention takes time and that it takes at least 50 msec to reach optimal performance in this situation no matter what the duration of the search array.

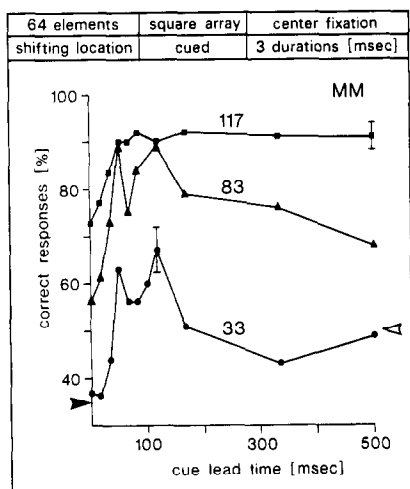


Fig. 7. Transient visual cuing experiment: performance as a function of cue lead time for 3 different stimulus durations (33, 83 and 117 msec). Cue and target could appear in any of the 64 target positions. The black and white arrow heads denote performance at 33 msec duration without cuing and with sustained cuing, respectively.

The most striking aspect of the data, however, is the fall-off in performance when the cue lead times were greater than 200 msec, which occurred in the two cases where the stimulus durations were relatively short (lower curves in Fig. 7). Not only is this fall-off apparent in the data, it is also readily apparent to the observer. From a phenomenological point of view, targets presented at the longer cue lead times are seen as much more indistinct in comparison to targets at the optimal cue lead times. This result came as a surprise to us since it would seem that the observer has the same information as to cue position 200 msec after cue onset as he does 80 msec after cue onset. Yet clearer perception of the target is apparent and good performance is obtained only at a range of optimal cue lead times.

Experiment 4: more eye movement controls

The rise and fall in performance happens over a very short span of time so that it seems highly unlikely that eye movements could account for any of the data at cue lead times of less than 150 msec because ordinary saccadic latencies are generally in the range of 200–220 msec. At cue lead times longer than saccadic latencies, however, the performance curves decline, although eye movements would tend to keep them up by improving discrimination. Thus, it is difficult to see how the presence of eye movements could have any effect on the shape of the curves seen in Fig. 7. Nevertheless, just to be sure, we conducted a pair of experiments on two observers where eye movements were monitored.

Figure 8 shows the results of NW (open symbols: with eye movement monitoring, filled symbols: without eye movement monitoring). Although there are some differences in performance levels for cue lead times greater than 100 msec, the basic qualitative pattern remains: the rise and fall of performance with increasing cue lead times is prominent in both cases. The same was true for the other subject in this experiment.

Experiment 5: effect of retinal eccentricity

The same down-turn in performance for longer cue lead times can be seen consistently in a parametric study where we asked the question: is this summoning of attention affected by the distance of the target from the fixation mark?

We conducted several sets of experiments, replacing the 64 element rectangular array with circular arrays, containing 10–18 targets, depending on the radius. With the circular

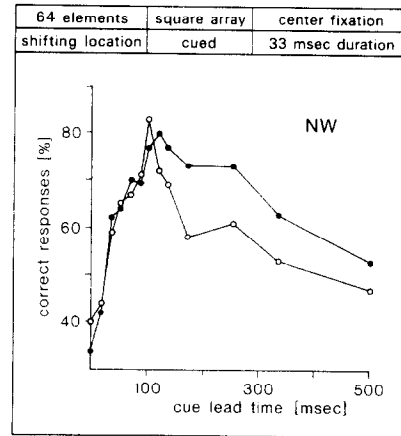


Fig. 8. The same pattern was seen in another subject (at 33 msec stimulus duration), with eye movement monitoring (solid symbols) and without (open symbols).

array, possible problems associated with differential visual acuity and contrast sensitivity for different retinal eccentricities were minimized. In the first set of experiments we ran 4 observers and 3 separate series employing circles with radii of 2, 4 and 6°. In every other respect, the situation was the same as described in Expt 3 and the performance vs cue lead time functions are also similar. Data for two observers are shown in Fig. 9.

Note that the 3 curves for each observer are qualitatively very similar, showing a steep rise in performance as the cue lead time increases up to about 50 msec. Also notable is the clear drop in performance for longer cue lead times at all 3 eccentricities.

One additional aspect of the experiment deserves comment. In the experiment using the 2° annulus, the size of the individual targets was small, subtending only 0.15° with a 1.26° inter-target spacing. This seemed like a small region within which to direct focal visual attention, as it has been claimed that the attentional "spotlight" is approx. 1° in diameter (Eriksen & Hoffmann, 1972; for a review see Johnston & Dark, 1986).

To press this issue, we diminished the angular extent of the annulus by increasing the viewing distance even more. The question was whether attention can be confined to the locus of closely spaced targets which are just resolvable and which are within the foveola, the center of the fovea. Here we used annuli with radii of 0.13, 0.25, 0.5, and 1° respectively, such that for the smallest annulus, the inter-target spacing was 0.09° or 5 min arc and the targets subtended only 2.5 min arc.

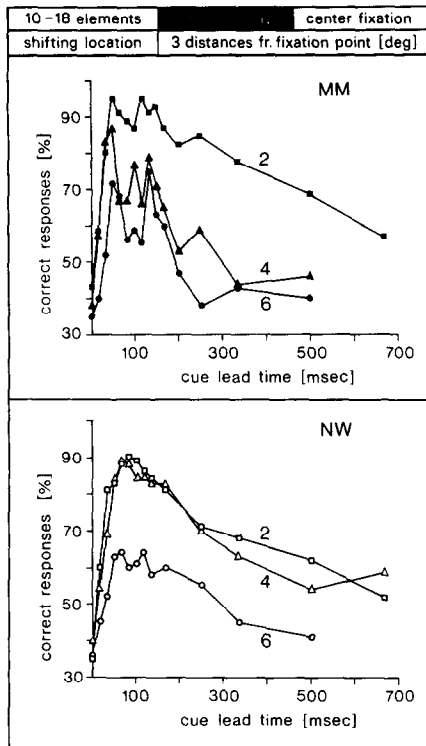


Fig. 9. Performance of two observers as a function of cue lead time for circular search arrays of 2, 4 and 6° of radius, containing 10, 12 and 18 elements, respectively. The stimulus duration was 17 msec for both observers.

Figure 10 shows the results, which look comparable to those obtained in more peripheral locations. All curves show an increase

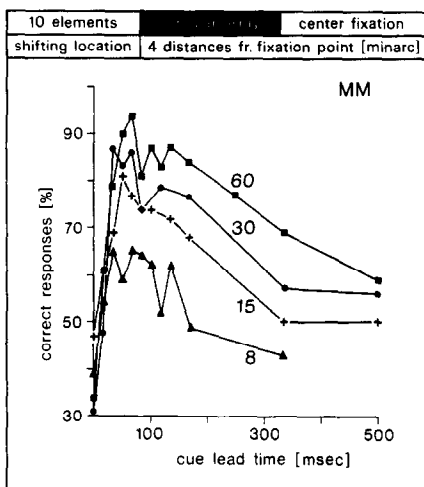


Fig. 10. Same as in Fig. 8 except circular arrays are smaller, mostly confined to the fovea. Numbers at the curves indicate the radius of the circle in arcmin. Because of the difficulty of the task increased with decreasing radius of the array, we compensated for that by increasing the stimulus duration. Consequently, they were 17 msec at 30 and 60 min arc, 33 msec at 15 min arc, and 50 msec at 8 min arc radius.

in performance up to a cue lead time of approximately 50 msec and a consistent drop in performance at cue lead times above 100 msec. Aside from replicating the transient improvement in performance, the data using the annulus with the smallest eccentricities indicate that this attentional enhancement can be confined to a tiny region in the visual field. In the most extreme case, attention appears to be confined to a small section of the fovea. Such conclusions are consistent with the findings of Julesz and Bergen (1983), who also found that scaling down of a search array to a much smaller size had essentially no effect on performance. Furthermore, this is at least indirect confirmation of studies indicating that the size of the attentional focus is dependent on the task (LaBerge, 1983; Eriksen & St James, 1986). However, we could not confirm an effect of distance (retinal eccentricity) on the latency of peak performance, as could have been predicted from the findings of Tsai (1983) and Shulman, Wilson and Sheehy (1985).

Discussion of experiments 3-5

In the previous section we have repeatedly demonstrated that at least one component of visual attention is transient. This means that it can be quickly summoned to a non-fixated site but that it cannot be held there. This is evident from the downturn of the curves at longer cue lead times in Figs 7-10. Despite this downturn, it should be clear that it still remains higher than when there was no cue present at all. This is indicated by the two arrows to the left and right of the lowest curve in Fig. 7: the solid arrow adjacent to the ordinate shows the performance level without any cue, and the open arrow at the right hand portion of the curve refers to performance when a cue was left on between trials.

From these data it should be evident that attention can have two components: a sustained component that can be moved voluntarily to a particular region, even in the absence of a cue, and a transient component which boosts performance above and beyond that attainable under sustained cuing conditions. We have shown that this transient component is time-locked to the cuing stimulus.

In the next series of experiments we explore the nature of the transient component, asking how it is related to expectancy and to the characteristics of the visual stimulus.

Experiment 6: the transient component is unaffected by prior knowledge of location

If our data indicating the separate existence of a sustained and a transient attentional component were correct, they should be experimentally separable. We reasoned that the data shown in Figs 7–10 indicate that even though the observer “understood” that the target would always appear at the cued location, this knowledge alone was not sufficient to obtain optimal performance. Performance was best during a short interval just following the introduction of the cue and degraded shortly thereafter. Thus, it seems to be caused by a more primitive transient process that is independent of awareness, but capable of boosting perception dramatically.

If we are correct in this interpretation, then prior knowledge of target position should have little or no effect on the transient component. To examine this issue, we conducted an additional experiment on two subjects to maximize prior knowledge by adding consistency. So, rather than changing position at random, the cue and target were *always* in the same location (the 3.5° position in Fig. 3). Otherwise the experiment was the same as before.

Figure 11 shows the results from this experiment. Most obvious is the characteristic rise and fall in performance as a function of cue lead time. Thus, prior knowledge resulting from consistency of cue position did not abolish the transient attentional effect. In fact, it appears that

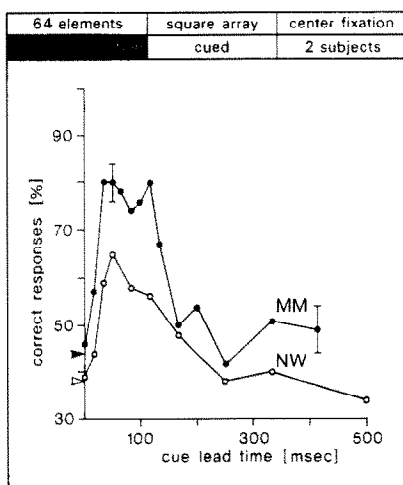


Fig. 11. Data for two observers show the effect of transient cuing when the cue is always at the same location (at 3.5° eccentricity as seen in Fig. 3). Note that the transient component remains. Arrows represent performance when there was no cue at all. Stimulus duration was 33 msec for observer MM and 50 msec for NW.

such a manipulation renders the cuing effect to be almost entirely transient. This can be appreciated by noting that performance for the longer durations falls to the level of the “no cue” condition (as denoted by the arrows on the ordinate). That the transient boost in performance was still present indicates independence from higher order knowledge of the situation or voluntary control.

Experiment 7: flicker does not abolish the downturn in performance

Such independence from “expectation” might suggest that the summoning of this transient component is tied to a local sensory discharge associated with the onset of the cue. This was suggested by Posner, Cohen and Rafal (1982) who reported a small rise in reaction times for longer cue lead times. Their view was that a transient component of attention could be directly attributable to the fact that even a steady cue is likely to have a transient response at its onset and this imparts a correspondingly brief enhancement of performance. Earlier, Breitmeyer and Ganz (1976) as well as Lennie (1980) suggested that retinal Y-cells, with their short latency and transient response pattern might mediate a primitive form of focal attention closely tied to a retinotopic locus. These interpretations imply that at least one component of attention is sensory in nature and closely linked to visual neurons particularly sensitive to transients.

If this were the case, one would predict that a cue maintaining the transient stimulation, say through flicker, would keep performance up for the duration of the flickering cue.

To test this prediction, we conducted the same experiment, modifying it only by having the cue go on and off intermittently at a frequency which is well within the frequency-following characteristics of visual neurons (7.5 Hz with a 50% duty cycle).

Figure 12 presents the data for two observers under these conditions, showing the rise and fall in performance for increasing cue lead times. Although it does appear that there may be some quantitative differences from the data presented earlier from subjects MM and NW, it is also clear that the “downturn” still persists and was not abolished by the existence of flicker. This indicates that the repetition of local sensory transients is not able to maintain attention at the cued locus. Thus, the existence of this decline in performance for the longer cue lead

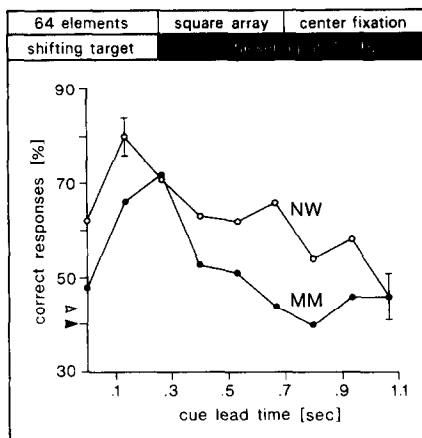


Fig. 12. The cue is flickered at 7.5 Hz, while stimulus duration was 50 msec. Note that in both subjects, the downturn in performance remains. The arrow heads at the ordinate show performance levels without cueing.

times argues against the view that the transient component of attention is directly related to the local neural transients associated with the cue.

Experiment 8: the “decoy” experiment—a local sensory transient is not necessary to summon transient attention

In the experiment to be described, we provide complementary evidence to show that the local sensory transient associated with cue onset is not the basis of the transient summoning of attention. This was accomplished by setting up a situation where no local sensory transient

exists at the cued site, yet where attentional cuing remains intact. To accomplish this goal, we started the trial by presenting the cue plus 7 additional boxes all indistinguishable from the real cue. These seven boxes acted as “decoys” and were unrelated to the target position. After a 1 sec period, the seven decoys were removed just leaving one red box which constituted the cue. The question is whether the existence of this remaining cue, which itself generates no local sensory transient, can summon the transient component of focal attention. The basic sequence of the experiment is described as the succession of frames depicted in Fig. 13.

The results from three observers demonstrate that such a cuing stimulus can evoke a transient attentional component. Figure 14 depicts the performance as a function of cue lead time and shows the pronounced rise and subsequent fall of performance in this case as well.

It should be noted, however, that the onset of the attentional shift is delayed in comparison to the other cuing situations. For example, note the performance of MC (open circles) and NW (open triangles) where the performance curve stays flat and does not rise at all for 80–100 msec, yet where the characteristic rise and fall is seen nevertheless.

Discussion of experiments 6–8

In these last 3 experiments we have shown that the transient component of focal attention remains intact under 3 very different conditions.

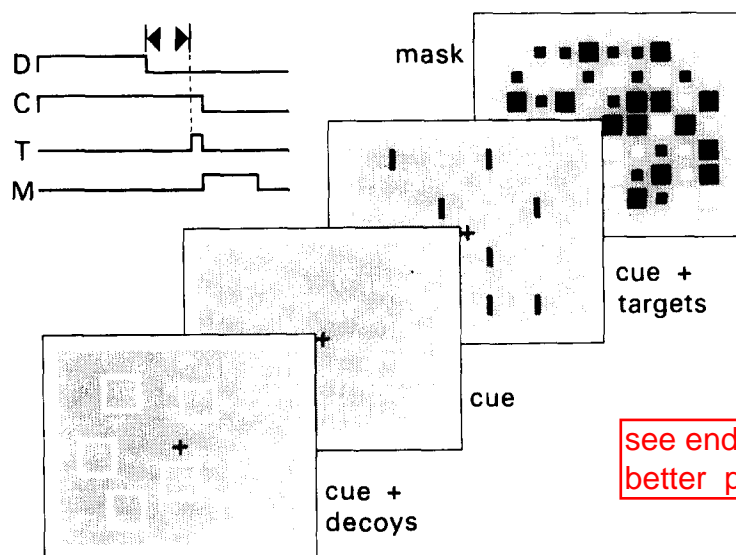


Fig. 13. Illustration of the “decoy” paradigm, where 8 cues are visible for a long time (1 sec). Then, 7 of them are removed (“decoys”) and the remaining one is valid indicating the critical location. Note that this sequence of stimulation does not induce any visual transient at the critical location before the array is presented.

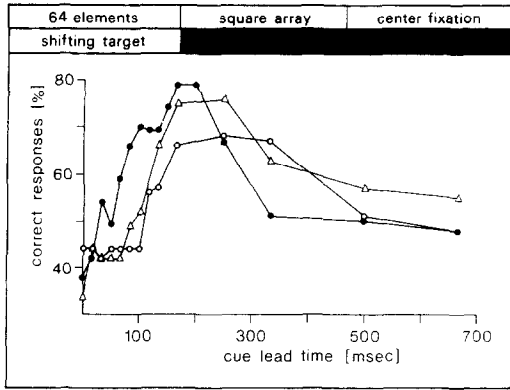


Fig. 14. Results of the "decoy" experiment (see Fig. 12) for 3 subjects (open triangles: MC; open circles: NW; solid circles: MM). Note that a transient component of attention is still apparent, although the cue does not introduce a visual transient at the critical location. Stimulus durations were 33 msec for MC and NW, 50 msec for MM.

It is unrelated to whether the target appears in the same place on repeated trials (experiment No. 6), it remains transient even though the cuing stimulus provides a steady succession of transients (experiment No.7), and finally, it can be elicited even when there is no local sensory transient at all (experiment No. 8).

These results show that the transient attentional process has a short time course and considerable autonomy, both, in relation to expectancy and to early visual processing.

Experiment 9: transient focal attention is independent of shape or paradigm

The studies reported so far use a very specific paradigm, borrowed from the tradition of visual search and requiring that the observers identify an odd orientation and color combination

amongst a set of distractors. To show that this transient attentional effect is more general and not confined to this particular paradigm, we report a final experiment where the stimulus configuration is very different.

In this experiment, we asked six observers to discriminate whether a vernier acuity target had its upper line displaced to the right or to the left. The target and 11 distractors (straight white lines) were arranged in a circle and presented on a black background, with a red disk cuing the critical location. So, rather than a 3-alternative forced-choice situation as described earlier, this is a 2-alternative decision.

The left part of Fig. 15 shows the vernier stimulus arrangement, while the right part shows data for one observer. It should be clear that, despite this change of paradigm, a rise and fall in performance is seen for increasing cue lead times. There is a relatively rapid rise in performance from near chance (here 50%) up to above 90%. Such an increase in performance, put in terms of discriminability units, is equivalent to a d' of 2.1 (Swets, 1964). It should be clear, however, that the time course of the curve for this task is much more prolonged than in the majority of the previously described experiments. The peak is at approx. 150 msec, later than that seen for the same observer (MM) in the conjunctive orientation-color task. This lengthening of the optimal cue lead for the vernier task was a consistent finding, also evident in all observers where both stimulus configurations were utilized.

The sequence of rise and fall in performance was seen in all 6 observers in the cued vernier task, indicating that transient attention is not

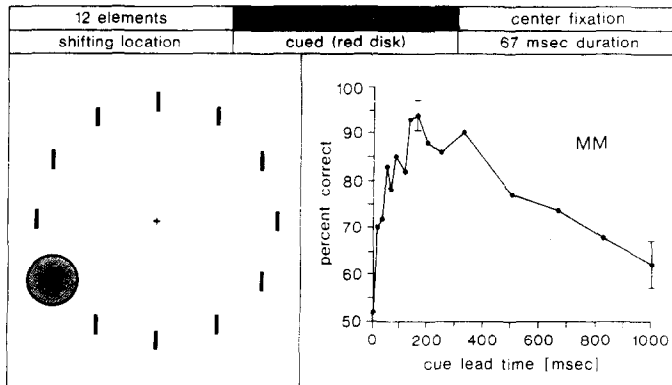


Fig. 15. Left: stimulus array for vernier acuity task. 11 out of 12 elements in an annulus of 5° radius were straight lines (64×6.7 min arc). The 12th element was a vernier target of the same dimensions and 3.3 min arc offset. A cue in the form of a red disk appeared at a variable time before the array of target and distractors, which was visible for 67 msec. Right: percentage of correct responses as function of cue lead time for subject MM.

dependent on a visual search paradigm using feature conjunctions. Hence, we suggest that it is a general phenomenon, not confined to a particular paradigm or stimulus configuration.

GENERAL DISCUSSION

Two Types of Attention

The results obtained in this investigation suggest the existence of at least two types of spatially directed attention, a sustained and a transient component. The schematic diagram in Fig. 16 summarizes our conception of these two components, indicating how their combination could result in the performance vs cue lead time functions seen in the present study. It is our view that both types of attention can lead to an improvement of performance, yet each appears differentially dependent on what is commonly described as "top-down" vs "bottom-up" processing.

The sustained component appears to be under voluntary or "top-down" control because we have shown that it can be directed to a blank region of the visual field at will (as shown in Fig. 5). It does not require a visible cue for its deployment.

The transient component, however, is very different. Prior knowledge or "expectancy" regarding target position has no influence on performance and it is not subject to voluntary control. This robust component is still obvious and more or less unchanged even if the cue appears in the same position for all trials (see Fig. 11). Thus, if a person knows that a target is to appear at a given locus, this fact alone does not materially affect performance. This lack of dependence on the observer's "expectancy" regarding stimulus location and its close time locking to the cuing event indicates that the transient component is more "primitive" and seemingly more closely tied to early visual processing. Unlike the sustained component, the transient component is not susceptible to "top-down" influences.

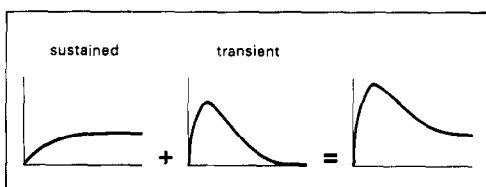


Fig. 16. Hypothetical summation of two attentional components with different time courses.

At the same time, however, our results indicate that the transient component is clearly distinct from and not directly related to the earliest stages of visual processing. The flickering cue experiment and the "decoy" experiment suggest that the transient component is only loosely coupled to early visual processing and that it is autonomous with respect to local sensory transients. One cannot link the deployment of this component of attention to specialized early visual processes such as transient visual channels as was suggested by others (Breitmeyer & Ganz, 1976; Lennie, 1980; Yantis & Jonides, 1984).

Neurophysiological Implications

Because these two components of attention can be distinguished by their susceptibility to "higher" vs "lower" order processing, we suggest that the two can be linked to different levels of cortical processing, which have rather precise meanings based on the pattern of intra- and inter-cortical connections (Maunsell & Van Essen, 1983; Van Essen & Maunsell, 1983; Jones, Coulter & Hendry, 1978). We suggest that the transient component of spatially directed attention is implemented at a relatively lower order cortical level, lower than the implementation of the sustained component.

Such a hypothesis could be tested directly. Neurophysiological experiments to date have not made a distinction between these two components and only the sustained component has been investigated. Clear effects of sustained attention have been seen at the level of areas V4 and IT (Richmond et al., 1983; Moran et al., 1985; Spitzer et al., 1988), as well as in the parietal cortex (Bushnell et al., 1981). No attentional effects have been seen in striate cortex (Wurtz et al., 1980; Moran & Desimone, 1985). Little work, however, has concentrated on intermediate areas. If our hypothesis was correct, neurophysiological correlates of the transient component of visual attention should occur at a lower cortical level than those of the sustained component. Thus, we suggest that neural correlates of transient visual attention would be seen at a site earlier than area V4, perhaps as early as V1. In this context, we suggest that our "decoy" experiment may be useful in neurophysiological experiments, because one could study the cell's response without subjecting it to the contaminating influence of a transient stimulus at the cued site.

One additional feature of the transient attentional data deserves special mention because it can help determine the size of the cortical substrate activated by focal attention. Our targets and the spacing between targets are relatively small as measured in terms of distance on the striate cortex. As an example, consider the case where the target array was an 8 min arc annulus with 3 min arc targets separated by 5 min arc (see Fig. 10). If we consider attention to be confined to the locus of a single element in this array, as demonstrated by Kröse and Julesz (1988), then such an area in the visual field at this eccentricity (8 min arc) is comparable to the size of a single hypercolumn in the striate cortex (Levi, Klein & Aitsebaomo, 1985). Single hypercolumns in human subtend approximately 1 square millimeter (Hitchcock & Hickey, 1980). Given the fact that the human striate cortex has an area of about 2000 times this size (Stensaas, Eddington & Dobbelle, 1974), the spatial selectivity of visual focal attention is quite remarkable.

Alternative Interpretations

For purposes of clarity, we have argued for one line of interpretation, that the transient boost in performance, although often closely time-locked with the stimulus, is not easily explained in terms of early sensory processes, nor is it explicable in terms of so-called "higher-order" voluntary processes. Instead, we see it as reflecting a transient visual attentional process, operating at an intermediate cortical level, having its own operating characteristics. We think our data, taken as a whole, support such a view. We acknowledge, however, that our interpretation might still be open to criticism and that alternative interpretations of individual experiments based on lower level (sensory) or higher levels of interaction could be raised. We mention some of these possible interpretations in turn.

For the flickering cue experiment (No. 7), one might argue that local visual units sensitive to the target and the cue are reciprocally inhibitory. Sensitization to the target might then be the result of a biphasic impulse response function of the cue since a target presented during the negative lobe of the cue response would be enhanced via disinhibition. In such a model, flickering the cue at its optimal temporal frequency would have no effect on the target enhancement, one could conceivably argue that the flicker rate of 7.5 Hz just coincides with the

end of a hypothetical biphasic impulse response function. Although this is a logical possibility, we note that the phenomenon of temporal interactions of stimuli has long been studied (see Breitmeyer, 1984) and no such process has been described.

Concerning the decoy experiment (No. 8), one might argue that although no direct local sensory transients occur with the offset of the decoy cues, interactions with more remote locations in the retina (McIlwain, 1964; Krueger, Fischer & Barth, 1975) might be able to change the gain of the retina at any stimulated site (even if it were a sustained response) and thus bestow the cued site with a small local transient. The evidence for this supposition, however, is weak. First, the argument assumes that such remote interactions are multiplicative (as opposed to additive), yet there is no indication that they are. Second, it should be remembered that in the decoy experiment, the cue has been left on for one second before the removal of the decoys. Thus, the response to the cue must be mediated by sustained mechanisms. Yet neurophysiological recordings from sustained cells in the primate lateral geniculate nucleus indicate no susceptibility to remote interactions (Blakemore & Vital-Durand, 1986). Finally, the very short latency (approx. 40 msec) of this remote activation in primates (Krueger et al., 1975) is not in accord with the prolonged delay of transient visual attention seen under these conditions.

In addition to the "sensory" interpretations, one could adopt a very different viewpoint and argue that the transient nature of visual attention is better explained in terms of higher level processes by considering the demands of the task. It has been hypothesized, for example, that the act of maintaining gaze at a fixation point requires at least some attentional resources (see Fischer, 1987). Because our observers were instructed to maintain fixation, it is possible that the cue draws attention to the periphery, but that the instruction to the observer forces him/her to shift attention back to the fixation mark.

Although this interpretation deserves additional investigation, we make two points that render such an argument less plausible. First, it would be rather surprising if the subjects' "effort of will" to maintain fixation would yield such abrupt temporal functions, showing precipitous drops in performance less than 100 msec after reaching peak performance. This is particularly evident in the data of MM (see

Figs 7, 9 and 11). Second is the fact that in another study (Mackeben & Nakayama, 1988) we still obtained the transient rise and fall in performance in a paradigm where the fixation point was extinguished just prior to the experimental trial. In that study, no central fixation point was available for the observer to draw his attention back to the center of the display, yet the decay function was just as pronounced.

Relation to Previous Work

The majority of experiments of visual attention in the past 20 yr have used reaction time as a measure of attention. Although a relatively consistent picture of attentional processing can be discerned using this paradigm (Johnston & Dark, 1986; Eriksen & Murphy, 1987; Yantis, 1988), we think the technique has disadvantages in comparison to the present approach, which make it less desirable as a method for future use. Two problems seem most limiting: first is the fact that a reaction time task does not dissociate a motor from a sensory component. By asking the observer to respond as quickly as possible, one runs the risk that the results may be influenced by a greater range of extraneous factors. Our use of a discrimination task where the observer has essentially unlimited time to make his decision provides a more direct access to visual attention because it decouples perception from the motor aspects of responding. Two recent studies have also used this approach with success (Downing, 1988; Kröse & Julesz, 1989). A second problem with the reaction time task is that it is not easily related to other psychophysical and neurophysiological measures. This may be of considerable importance when trying to relate changes in tuning properties of single cells (Spitzer et al., 1988) with attentional shifts. We think that this could be more easily achieved by measuring discrimination performance.

Despite these potential problems associated with reaction time experiments, however, there is some agreement on at least one major point: both types of data *can* show a transient component of attention. In a few cases, a shortening of reaction times for cue lead times of 100–300 msec and a very subtle lengthening for longer cue lead times have been reported (Posner et al., 1982; Remington & Pierce, 1984; Maylor, 1985). We attribute the large quantitative difference between those data and our own to the much greater demand put on discrimination performance in our paradigm (in respect to spatial resolution, stimulus duration,

and number of possible locations), which necessitates activation of perceptual resources not challenged in those previous studies.

Unresolved Questions

We would like to note two observations which deserve additional clarification. The first question pertains to the conditions under which the rise and fall of transient attention is apparent. Although not addressed directly in this paper, it should be clear from the top curve in Fig. 7 that the “down-turn” in performance is not always present (Lyon, 1987). In the data shown, there is no down-turn in performance for the longest stimulus presentation duration. One possibility is that the lack of a performance downturn in easier tasks is due to a “ceiling” artifact because the underlying process responsible for the transient rise is “clipped.”

The second question pertains to the exact time course of the transient component. In general we have found that attention peaks somewhere around 80–100 msec cue lead time, although it can be somewhat variable. We consistently find that the optimal cue lead time is considerably longer in the vernier acuity task, although the finding has not been detailed here. Since the spatial scale required for the vernier acuity task may be higher than for the vertical vs horizontal bar discrimination, it might be reasonable to suppose that it could take more time to narrow down the focus of attention for a high acuity target. As yet, however, we have no additional data which would support such conjecture.

Functional Considerations

In this section we briefly touch upon two functional implications of the results obtained.

First we consider the duration of the focal attention process. Its time course is somewhat at odds with currently held views of visual attention. Julesz (1984) as well as Treisman (1985) postulate a quick redirection of attention, concluding that in visual search tasks, attention can jump from item to item in 30–40 msec intervals. The relatively long duration of transient attention reported here may be inconsistent with such a view although it should also be noted that the task demands in our study are very different from those in standard visual search tasks where no cue is present.

The second consideration concerns the involuntary nature of transient visual attention. By involuntary we mean its quasi-reflex quality, its

manifestation even when the observer knows from trial to trial that the target will appear in the same locus on the display. From a functional perspective, it would seem that such a mechanism of automatically drawing attention to a particularly salient portion of the visual display would be very helpful, providing automatic processing for distinct features in the visual field (see Julesz, 1984). Yet it would also have its drawbacks. The basically involuntary nature of this attentional deployment could be dangerous to the organism, particularly if it is engaged in a task which requires sustained focal attention in a different location. Thus, it is perhaps apt that an involuntary component of attention be highly transient. This way, it does not last long enough to jeopardize visual perception elsewhere in the visual field.

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REFERENCES

- Allman, J., Miezin, J. & McGuiness, E. (1985). Stimulus specific responses from beyond the classical receptive field: Neurophysiological mechanisms for local-global comparisons in visual neurons. *Annual Reviews, Neuroscience*, 8, 407–429.
- Anstis, S. M. (1974). A chart demonstrating variations in acuity with retinal position. *Vision Research*, 14, 589–592.
- Bashinski, H. S. & Bacharach, V. R. (1980). Enhancement of perceptual sensitivity as the result of selective attending to spatial locations. *Perception and Psychophysics*, 28, 241–248.
- Bergen, J. R. & Julesz, B. (1983). Rapid discrimination of visual patterns. *IEEE Transactions on Systems Man and Cybernetics, SMC-13*, 857–863.
- Blakemore, C. & Tobin, E. A. (1972). Lateral inhibition between orientation detectors in the cat's visual cortex. *Experimental Brain Research*, 15, 439–440.
- Blakemore, C. & Vital-Durand, F. (1986). Organization of post-natal development of the monkey's lateral geniculate nucleus. *Journal of Physiology, London*, 380, 453–491.
- Breitmeyer, B. G. (1984). *Visual masking: An integrative approach*. Oxford: Oxford University Press.
- Breitmeyer, B. G. & Ganz, L. (1976). Implications of sustained and transient channel for theories of visual pattern masking, saccadic suppression and information processing. *Psychology Review*, 83, 1–36.
- Brown, B., Adams, A. J., Jampolsky, A. & Muegge, M. (1977). A clinically useful eye movement recording system. *American Journal of Optometry and Physiological Optics*, 54, 56–60.
- Bushnell, M. C., Goldberg, M. E. & Robinson, D. L. (1981). Behavioral enhancement of visual responses in monkey cerebral cortex. I. Modulation in posterior parietal cortex related to selective visual attention. *Journal of Neurophysiology*, 46, 755–772.
- DeYoe, E. A. E., Knierim, J., Sagi, D., Julesz, B. & Van Essen, D. (1986). Single unit responses to static and dynamic texture patterns in macaque V2 and V1 cortex. *Investigative Ophthalmology and Visual Sciences*, 27 (Suppl.), 18.
- Downing, C. J. (1988). Expectancy and visual-spatial attention: Effects on perceptual quality. *Journal of Experimental Psychology: Human Perception and Performance*, 14, 188–202.
- Eriksen, C. W. & Hoffmann, J. E. (1972). Some characteristics of selective attention in visual perception determined by vocal reaction time. *Perception and Psychophysics*, 11, 169–171.
- Eriksen, C. W. & Murphy, T. D. (1987). Movement of attentional focus across the visual field: A critical look at the evidence. *Perception and Psychophysics*, 42, 299–305.
- Eriksen, C. W. & St James, J. D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception and Psychophysics*, 40, 225–240.
- Fischer, B. (1987). The preparation of visually guided saccades. *Reviews in Physiology and Biochemical Pharmacology*, 106, 1–35.
- Frost, B. J. & Nakayama, K. (1983). Single neurons code opposing motion independent of direction. *Science, New York*, 220, 744–745.
- Frost, B. J., Scilley, P. L. & Wong, S. C. P. (1981). Having background patterns reveal double opponency of directionally specific pigeon tectal neurons. *Experimental Brain Research*, 43, 173–185.
- Grindley, C. G. & Townsend, V. (1968). Voluntary attention in peripheral vision and its effects on acuity and differential thresholds. *Quarterly Journal of Experimental Psychology*, 20, 11–19.
- Hayes, W. L. (1973). *Statistics for the social sciences* (2nd edn). New York: Holt, Rinehart & Winston.
- Helmholtz, H. von (1896). *Handbuch der Physiologischen Optik, Dritter Abschnitt, Zweite Auflage*. Hamburg, Voss.
- Hitchcock, P. F. & Hickey, T. L. (1980). Ocular dominance columns: Evidence for their presence in humans. *Brain Research* 182, 176–179.
- Johnston, W. A. & Dark, V. J. (1986). Selective attention. *Annual Review of Psychology*, 37, 43–75.
- Jones, E. G., Coulter, J. D. & Hendry, S. H. C. (1978). Intracortical connectivity of architectonic fields in the somatic sensory, motor, and parietal cortex of monkeys. *Journal of Comparative Neurology*, 181, 291–348.
- Julesz, B. (1984). Toward an axiomatic theory of preattentive vision. In Edelman, G. M., Gall, W. E. & Cowan, W. M. (Eds.) *Dynamic aspects of neocortical function*. New York: Neurosciences Research Foundation.
- Julesz, B. & Bergen, J. R. (1983). Textons, the fundamental elements in preattentive vision and perception of textures. *Transactions of the IEEE, Systems, Man and Cybernetics, SMC-13*, 857–863.
- Koch, C. & Ullman, S. (1985). Shifts in selective visual attention: Towards the underlying neural circuitry. *Human Neurobiology*, 4, 219–227.
- Kröse, B. J. A. & Julesz, B. (1989). The control and speed of shifts of attention. *Vision Research*, 29, 1607–1619.

- Krueger, J., Fischer, B. & Barth, R. (1975). The shift-effect in retinal ganglion cells of the rhesus monkey. *Experimental Brain Research*, 23, 443–446.
- LaBerge, D. (1983). Spatial extent of attention to letters in words. *Journal of Experimental Psychology, Human Perception and Performance*, 9, 371–379.
- Lennie, P. (1980). Parallel visual pathways: A review. *Vision Research*, 20, 561–594.
- Levi, D. M., Klein, S. A. & Aitsebaomo, A. P. (1985). Vernier acuity, crowding and cortical magnification. *Vision Research*, 25, 963–977.
- Lyon, D. R. (1987). How quickly can attention affect form perception. Air Force Human Resources Laboratory, Final Technical Report, November.
- Mackeben, M. & Nakayama, K. (1988). Fixation release facilitates rapid attentional shifts. *Investigative Ophthalmology and Visual Sciences*, 29 (Suppl.), 22.
- Maunsell, J. H. R. & Van Essen, D. C. (1983). The connections of the middle temporal visual area (MT) and their relationship to cortical hierarchy in the macaque monkey. *Journal of Neuroscience*, 3, 2563–2686.
- Maylor, E. A. (1985). Facilitory and inhibitory components of orienting in visual space. In Posner, M. I. & Marin, O. S. M. (Eds.) *Attention and performance*. Hillsdale, N.J.: Erlbaum.
- McIlwain, J. T. (1964). Receptive fields of optic tract axons and lateral geniculate cells: Peripheral extent and barbiturate sensitivity. *Journal of Neurophysiology*, 27, 1154–1173.
- Mertens, J. J. (1956). Influence of knowledge of target locations upon the probability of observation of peripherally observable test flashes. *Journal of the Optical Society of America*, 46, 1069–1070.
- Moran, J. & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Science, New York*, 229, 782–784.
- Mower, O. H. (1941). Preparatory set (expectancy): Further evidence of its central locus. *Journal of Experimental Psychology*, 28, 116–133.
- Nakayama, K. (1989). The iconic bottleneck and the tenuous link between early visual processing and perception. In Blakemore, C. (Ed.), *Visual coding and efficiency*. Cambridge: Cambridge University Press, In press.
- Nakayama, K. & Silverman, G. H. (1986a). Serial and parallel processing of visual feature conjunctions. *Nature, London*, 320, 264–265.
- Nakayama, K. & Silverman, G. H. (1986b). Serial and parallel encoding of visual feature conjunctions. *Investigative Ophthalmology and Visual Sciences* (Suppl.).
- Neisser, U. (1967). *Cognitive psychology*. New York: Appleton-Century Crofts.
- Nelson, J. I. & Frost, B. J. (1978). Orientation selective inhibition from beyond the classical receptive field. *Brain Research*, 139, 359–365.
- Petersen, S. E., Robinson, D. L. & Morris, J. D. (1987). Contributions of the pulvinar to visual spatial attention. *Neuropsychologia*, 25 (1A), 97–105.
- Posner, M. I. & Cohen, M. L. (1984). Components of visual orienting. In Bouma, H. & Bowhuis, D. (Eds.) *Attention and performance* (pp. 531–556). Hillsdale, N.J.: Erlbaum.
- Posner, M. I., Snyder, C. R. R. & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General*, 109, 160–174.
- Posner, M. I., Cohen, Y. & Rafal, R. D. (1982). Neural systems control of spatial orienting. *Philosophical Transactions of the Royal Society, London B*, 298, 187–198.
- Remington, R. & Pierce, L. (1984). Moving attention: Evidence for time-invariant shifts of visual selective attention. *Perception and Psychophysics*, 35, 393–399.
- Richmond, B. J., Wurtz, R. H. & Sato, T. (1983). Visual responses of inferior temporal neurons in the awake rhesus monkey. *Journal of Neurophysiology*, 50, 1415–1432.
- Shaw, M. L. (1984). Division of attention among spatial locations: A fundamental difference between detection of letters and detection of luminance increments. In Bouma, H. & Bowhuis, D. G. (Eds.) *Attention and performance* (Vol. 10, pp. 109–121). Hillsdale, N.J.: Erlbaum.
- Shulman, G. L., Wilson, J. & Sheehy, J. B. (1985). Spatial determinants of the distribution of attention. *Perception and Psychophysics*, 37, 59–65.
- Sperling, G. (1984). A unified theory of attention and signal detection. In Parasuraman, R. & Davies, D. R. (Eds.) *Varieties of attention*. New York: Academic Press.
- Spitzer, H., Desimone, R. & Moran, J. (1988). Increased attention enhances both behavior and neural performance. *Science, New York*, 240, 338–340.
- Stensaas, S., Eddington, D. K. & Dobbelle, W. H. (1974). The topography and variability of the primary visual cortex in man. *Journal of Neurosurgery*, 40, 747–755.
- Swets, J. A. (ed.) (1964). *Signal detection and recognition by human observers*. New York: Wiley.
- Treisman, A. M. (1985). Preattentive processing in vision. *Computer Vision, Graphics and Image Processing*, 31, 156–177.
- Treisman, A. M. & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, 12, 97–136.
- Tsal, Y. (1983). Movements of attention across the visual field. *Journal of Experimental Psychology: Human Perception and Performance*, 9, 523–530.
- Van Essen, D. C. & Maunsell, J. H. R. (1983). Hierarchical organization and the functional streams in the visual cortex. *Trends in Neuroscience*, 370–375.
- Van Voorhis, S. T. & Hillyard, S. A. (1977). Visual evoked potentials and selective attention to points in space. *Perception and Psychophysics*, 22, 54–62.
- Virsu, V. & Rovamo, J. (1979). Visual resolution, contrast sensitivity, and the cortical magnification factor. *Experimental Brain Research*, 37, 475–494.
- Wurtz, R. H., Goldberg, M. E. & Robinson, D. L. (1980). Behavioral modulation of visual responses in the monkey: Stimulus selection for attention and movement. *Progress in Psychobiology and Physiology*, 9, 43–83.
- Yantis, S. (1988). On analog movements of visual attention. *Perception and Psychophysics*, 43, 203–206.
- Yantis, S. & Jonides, J. (1984). Abrupt visual onsets and selective attention: evidence from visual search. *Journal of Experimental Psychology: Human Perception and Performance*, 10, 601–621.

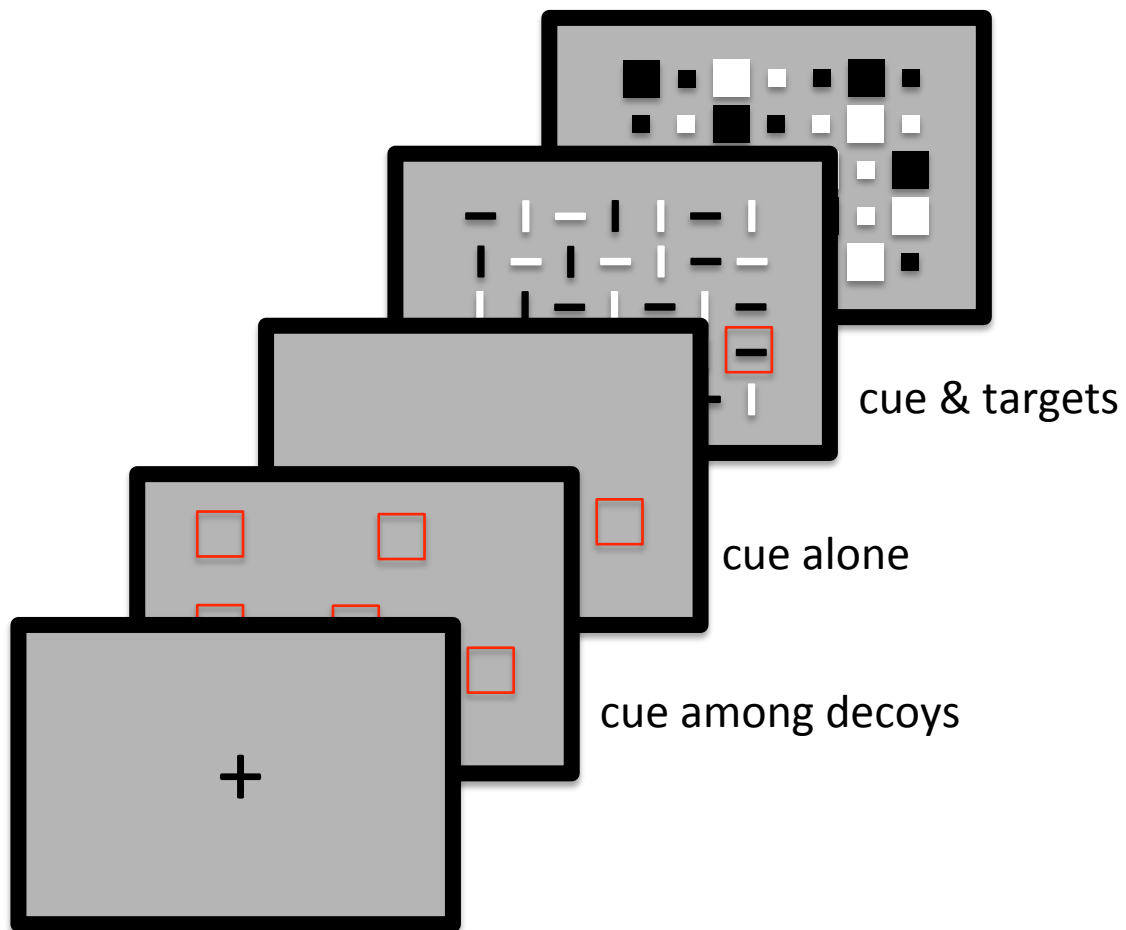


Fig. 13. Illustration of the "decoy" paradigm, where 8 cues are visible for a long time (1 sec). Then, 7 of them are removed ("decoys") and the remaining one is valid indicating the critical location. Note that this sequence of stimulation does not induce any visual transient at the critical location before the array is presented.