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Research carried out over a three-year period on several interrelated topics is described in this report. These projects are all in the area of visual cognition, and focus on feature and object perception, models of selective attention, and the nature of visual routines such as curve tracing and subitizing. The major thrust of this endeavor has been to explore the nature of visual processes to determine the extent to which they are carried out in parallel or in series.

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22a. NAME OF RESPONSIBLE INDIVIDUAL: Dr. Alfred R. Fregly

22b. TELEPHONE (Include Area Code): (202) 767-5021

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Preattentive and Attentive Visual Information Processing

In Interim Reports of June, 1988 and June, 1989 several projects were described in detail. In this Final Report just the highlights of those earlier reports will be described, in addition to a more detailed presentation of the work accomplished in the third year of the project. The "highlights" referred to here will be the abstracts of the major published papers that resulted from our work.

Years 1 and 2

1. Folk, C.L., Egeth, H., & Kwak, H. (1988). Subitizing: Direct apprehension or serial processing? Perception & Psychophysics, 44, 313-320.

Tasks involving the judgment of numerosity in the subitizing range (1-5 elements) typically yield small but significant variations in performance as a function of the number of elements. Such a result is consistent with the existence of a serial component of numerosity processing in the subitizing range. In 1985, Sagi and Julesz reported the results of a subitizing task in which performance remained virtually constant as numerosity was varied. Three experiments are reported that explore this discrepancy. The results indicate that the discrepancy is not due to the nature of the stimuli, presentation mode, dependent measure, or level of practice used by Sagi and Julesz. All conditions showed variations in performance as a function of target numerosity. Our results are consistent with models that assume that there is a serial component to subitizing.

2. Mullin, P.A., Egeth, H.E., & Mordkoff, J.T. (1988). Redundant-target detection and processing capacity: The problem of positional preferences. Perception & Psychophysics, 43, 607-610.

One means of determining whether processing is serial or parallel is the redundancy-gain paradigm. If mean reaction time is faster with redundant targets than with a single target, then certain classes of serial models may be ruled out. However, there are artifacts, such as favored-position effects, that can lead to this apparent redundancy gains even though processing is serial. In this paper we examine a method that has been proposed for detecting when data have been produced by a fovored position effect. Our conclusion is that the published method is inadequate. This means that data from the redundancy-gain paradigm needs to be treated with considerable caution.

3. Folk, C.L. & Egeth, H.E. (1989). Does the identification of simple features require serial processing? Journal of Experimental Psychology: Human Perception and Performance,

15, 97-110.

Several recent studies have shown performance decrements with increasing display size when background texture elements are present in a same-different feature discrimination task-a result that challenges the traditional notion that the identities of simple visual features are processed in parallel, preattentively. Four experiments are reported that explore the implications of these results. Experiment 1 replicates the recent studies but limits the generalizability of the results to small target numbers. Experiments 2 and 3 show that the observed performance decrements are not due to a serial or even limited-capacity, parallel process. Experiments 4 suggests that decision factors idiosyncratic to the use of texture elements in a same-different task are responsible for the effect. It is concluded that the identification of simple visual features proceeds in parallel, with unlimited capacity (i.e., preattentively).

4. Mullin, P.A. & Egeth, H.E. (1989). Capacity limitations in visual word processing. Journal of Experimental Psychology: Human Perception and Performance, 15, 111-123.

The ability of subjects to process English words in a spatially parallel manner was examined in several redundant-target detection tasks. When redundant targets were identical in a given display, processing limitations were evident in a task that required subjects to make semantic categorizations of words. However, parallel processing of identical redundant target words was exhibited in a lexical decision task that required a structural analysis of letter strings, but not an analysis of word meaning. The difference in performance in the two tasks suggests that the capacity for semantic processing is limited. Analysis designed to examine whether the redundancy gain in Experiment 2 could be attributed to limited capacity processing in conjunction with positional preferences provided evidence against this possibility. In addition, these analyses suggested that the processing times for the redundant targets in Experiment 2 might be positively correlated. In the third and fourth experiments, the redundant-target display contained two different words. Processing interference, in the form of a redundancy loss, was evident in the lexical decision task, but not in the semantic categorization task, confirming a difference in the mode of processing between the two tasks. The results provide evidence against the unlimited-capacity, parallel processing hypothesis of late selection theories of attention.

5. Pringle, R. & Egeth, H.E. (1988). Mental curve tracing with elementary stimuli. Journal of Experimental Psychology: Human Perception and Performance, 14, 716-728.

It has been proposed that certain spatial relations are determined by an operation, or "visual routine", that can trace along a boundary (Ullman, 1984). This proposal was supported by Jolicoeur, Ullman, and Mackay's (1986) finding that the time required to determine if two Xs are on the same curve increased monotonically with the separation of the Xs along that curve. In the present study the generality of the curve tracing hypothesis was explored across four experiments by using elementary stimuli that eliminated interweaving curves, displaced the fixation point away from the curves and target Xs, and provided a simple alternative to curve tracing-namely, determining whether or not the Xs fell on the same side of the figure. Stimuli consisted of two curves (150 arcs) and two Xs, and each stimulus was presented for 150 ms. In Experiments 1 and 2, subjects were instructed to decide as quickly as possible if the two Xs fell on the same curve or on different curves. Even for these elementary stimuli, mean reaction time (RT) for same trials increased monotonically with distance separating the Xs. In Experiments 3 and 4 alternatives to curve tracing were tested. For same trials the evidence strongly favored curve tracing. However, different trials were apparently solved on the basis of judgmental processes presumbaly operating in parallel with curve tracing. Curve tracing rates fluctuated across experiments and seemed to be partially governed by the width of the "pathway" provided for the trace.

6. Egeth, H. E., Folk, C. L., & Mullin, P. A. (1989). Spatial parallelism in the processing of lines, letters, and lexicality. In B. E. Shepp & S. Ballesteros, Object perception: Structure and process. Hillsdale, N.J.: Erlbaum.

This is a chapter that provides an overview of our efforts to assess processing mode in a variety of stimulus domains. It essentially covers material discussed in papers 3 and 4, above, with the addition of some original material.

Year 3

During this year several major projects were brought to completion.

1. Bacon, W. F. & Egeth, H. E. Local processing in preattentive feature detection. Journal of Experimental Psychology: Human Perception and Performance, in press.

Does the processing of features in the visual field somehow depend on the presence of other features? What is the extent of this interdependence? Recently, there has been a claim of a rather profound sort of interdependence. Specifically, it has been claimed that in order for a feature to be detected preattentively (in parallel), it must be possible to compute a feature gradient between that feature and a neighboring stimulus. In other words, a target will not be detected preattentively unless it is within some small critical distance of a nontarget.

This claim was made by Sagi and Julesz (1987), on the basis of findings from a same/different task in which they varied the density of the element display. In their task, subjects searched for a line segment of known orientation against a background of line segments of some other orientation. There were two display configurations. In the large minimal interline spacing condition, the display consisted of a 7 x 7 array of possible element locations. In the small minimal interline spacing condition, the display consisted of a 10 x 10 array of possible element locations, squeezed into approximately the same space. Stimuli were presented briefly, and after some stimulus onset asynchrony (SOA), followed by a pattern mask. The performance measure was percentage correct. They found that for both display configurations, performance declined from a display size of 2 to a display size of around 30. However, at that display size, performance on the two configurations began to diverge. In the large minimal interline spacing condition, performance continued to decline up through the largest display size. However, in the small minimal interline spacing condition, performance began to improve, and continued to improve up to the largest possible display size. The investigators note that this improvement can be predicted on the basis of the increasing probability that there will be a nontarget within two degrees of visual angle from the target. Therefore, they conclude that feature detection has a short-range limitation. If these conclusions are correct, they would have important theoretical implications. They bring into question the whole notion of searching for features by monitoring feature maps.

However, other interpretations of the Sagi and Julesz results are possible. Since Sagi and Julesz had to infer target-nontarget separation from display size and density, it is possible that their findings were caused by some other factor that varied with display size, such as nontarget-nontarget separation, which might be responsible for nontarget grouping. In order to disentangle these factors, Bacon and I have conducted a series of experiments (in both the same-different and present-absent paradigms) in which we independently manipulated the target-nontarget separation and the display size. We used square patches of color as stimuli and varied the number of elements from 2 to 32. Target-nontarget separation was controlled by choosing the location for the target first, and then placing constraints on the possible locations of the nontargets. Thus, target-nontarget separation did not necessarily decrease as display size increased, because the window of locations around the target was directly controlled in the experiment. If in fact there is a short-range limitation in feature detection, then at any given display size, performance should decline as separation increases.

We found that mean RT's were essentially identical whether separation was small (.6 deg) intermediate (2.0 deg) or large (3.4 deg). Since separation was manipulated directly, rather than inferred from element numerosity, this is strong evidence against a short-range limitation. Not only was there no evidence of a qualitative change in processing (i.e., from parallel to serial) at large separation, there was no evidence of any kind of dependence on local processes (i.e., not even a hindered parallel process).

Further, we found an inverse relationship between RT and numerosity. Note that it was this very relationship that led Sagi and Julesz (1987) to assert the importance of target-nontarget proximity. It is interesting that our task still showed this effect, even though the correlation between numerosity and target-nontarget separation has been experimentally eliminated. This suggests that the improved performance with increasing numerosity that we and Sagi and Julesz found must be due to some other factor (other than target-nontarget separation) that varies with numerosity.

Further experiments have shown similar effects with less discriminable color pairs, and with easy and difficult orientation discriminations. We have also explored the basis of the inverse relation between RT and display size. Specifically, nontarget grouping was explored and found to be a crucial determinant of performance.

2. Egeth, H. E. & Dagenbach, D. Parallel versus serial processing in visual search: Further evidence from subadditive effects of visual quality. Journal of Experimental Psychology: Human Perception and Performance, in press.

There is general agreement that at least two different modes of information processing may be distinguished--parallel and serial. However, it is quite difficult to unambiguously characterize processing mode in specific situations. For example, one diagnostic entails measuring reaction time as a function of the number of elements in a visual display. If reaction time is independent of display size, this is often taken as evidence of parallel processing; if it increases linearly with display size, processing is often taken to be serial. However, any such diagnostic has problems (see, e.g., Townsend, 1974, 1990). Thus, it seems clear that having a variety of diagnostics could be useful in that the results from the application of several different diagnostics may provide converging operations for the characterization of processing mode. To this end, a new diagnostic is proposed that may prove useful. The particular venue for this investigation is visual search, but the general logic can be applied elsewhere as well.

The proposed diagnostic is in a sense a variation on themes developed earlier in the study of mental chronometry. More specifically, it is related to ideas proposed by Sternberg (1969a), by Schweikert (1978) and by Townsend & Ashby (1983). It entails manipulating the processing speed for elements in a visual display by varying visual quality. However, the present method differs from previous investigations using visual quality, such as that of Pashler & Badgio (1985), by having the key variations in visual quality occur within a trial, rather than between trials.

The diagnostic is developed here for the simple case where there are two elements per display in a search task. In this case, some straightforward predictions that distinguish between parallel and serial processing can be made for response times on target-absent trials, wherein processing is assumed to be exhaustive.

Imagine a search task with X defined as the target and O the nontarget. Displays consist of just two elements. Thus for this simple experiment the possible stimuli are: XX, XO, OX, OO. The first three stimuli each contain a target (X), and thus should get a positive response, e.g., the verbal response "present"). The fourth example contains no target character and should thus get a negative response (e.g., the verbal response "absent"). There is one additional manipulation; each character is either of high or low "quality." For example, a stimulus might consist of a bright X and a dim O.

Consider the three possible kinds of displays that can occur on target-absent trials with two elements when visual quality is manipulated: (1) Both distractor items may be low in quality, (2) one distractor may be high in quality and one may be low in quality, or (3) both may be high in quality. Assume that the processing time required to identify a character that is high in quality is $\underline{T}$, and that the processing time required to identify a character that is low in quality is $\underline{T}$ plus another value representing the slowing due to the degradation of the stimulus, $\Delta\underline{T}$.

For the serial model total reaction time consists of some base time that we ignore here plus the time required to process each stimulus in turn. These values are as follows: for two high quality stimuli $\underline{T} + \underline{T}$, or $2\underline{T}$; for mixed quality it is the same $2\underline{T}$ plus an increment $\Delta\underline{T}$ for the degraded stimulus; for two low quality stimuli it is $2\underline{T} + 2\Delta\underline{T}$. For the parallel model, the time to process two high quality stimuli simultaneously is taken to be $\underline{T}$. When one of them is degraded there is an increment, $\Delta\underline{T}$, in processing time. When both are degraded the time should still be $\underline{T} + \Delta\underline{T}$ because the stimuli are being processed in parallel. Thus the two models predict two different patterns of results. The serial model predicts additivity of RTs as more low quality stimuli are added to a display; the parallel model predicts underadditivity.

This diagnostic was evaluated in two experiments wherein parallel and serial processing might be expected on the basis of previous work, and was then applied to a more uncertain case in a third experiment. The diagnostic indicates parallel processing of stimuli that differ from each other on a featural basis (X's and O's) and canonical letters that differ in line arrangement (T's and L's), but serial processing when T's and L's were randomly rotated. These results form a coherent pattern that is understandable in terms of the literature on visual search, and thus suggest that the diagnostic may be a useful addition to the methodology used to distinguish between serial and parallel processes.

3. Kwak, H. Dagenbach, D., & Egeth, H. Further evidence for a time-independent shift of the focus of attention. Perception & Psychophysics, submitted.

This experiment provided the first independent use of the diagnostic introduced above. The substantive question at issue was whether attention moves in an analog fashion. A review of the literature showed that the existing evidence is contradictory. In our research, the separation between stimuli was manipulated in a same-different matching task. In Experiment 1 stimuli were upright T's and/or L's, whereas in Experiment 2 they were rotated T's and/or L's. In both experiments mean reaction time (RT) for the same-different judgement was constant across the levels of interletter distance, suggesting that either the time needed to move attention between stimuli was independent of distance, or that the stimuli were processed in parallel. These alternatives were tested in two further experiments using a diagnostic for parallel processing proposed by Egeth and Dagenbach (1989). The diagnostic indicated that the independence of RT and separation obtained in Experiment 1 could be due to parallel processing of the two stimuli, but that the rotated T's and L's in Experiment 2 were processed serially. If serial processing implies the utilization of attention, then the independence of RT and separation in Experiment 2 implies that attention does not take more time to move a greater distance.

4. Dagenbach, D. & Egeth, H. Using converging operations to test for parallel processing. To be presented at the 1990 meeting of the Psychonomic Society; journal ms. in preparation.

In this set of experiments we attempt additional validation of the subadditivity diagnostic. We sytematically manipulate load (display size) and visual quality. The question is simply whether we get consistent results when we examine two aspects of the data from the same experiment, i.e., the effect of load on mean RT and the effect of quality manipulation on mean RT. The initial results (to be presented at the meeting of the Psychonomic Society in November, 1990) suggest just such convergence. In conditions that give rise to no load effect we get subadditivity from the quality manipulation; in conditions that give rise to a substantial load effect we get additivity from the qulaity manipulation.

5. Egeth, H. E. & Mordkoff, J. T. (in press). Redundancy gain revisited: Evidence for parallel processing of separable dimensions. In J. Pomerantz & G. Lockhead (Eds.), The perception of structure. Washington, D. C. American Psychological Association.

Mordkoff, J. T., Yantis, S. & Egeth, H. E. (1990). Detecting conjunction of color and form in parallel. Perception & Psychophysics, 48, 157-168.

According to feature-integration theory (e.g., Treisman & Gelade, 1980), when subjects search for a target defined in terms of a conjunction of several separable dimensions, such that each nontarget shares a feature with the target, then each display element must be examined in turn until the target is found. The usual method for assessing whether search is serial and self-terminating is to measure reaction time as a function of display numerosity. However, serious problems with this methodology have been pointed out (e.g., Townsend, 1972). In the present experiments subjects indicated whether a specific target element was present; on some trials two targets were presented. Analysis of the reaction-time distributions using a method introduced by Miller (1982) indicated that the decrease in reaction time found on dual-target trials was too great to be compatible with any sort of serial-decisions model (as well as certain varieties of parallel models). We conclude that at least two objects may simultaneously have their color and form conjoined into unified percepts.

For the interested reader, Miller's method is described briefly here. the basic idea is that activation from separate channels may combine to satisfy a single criterion for response initiation. This is what Miller has referred to as coactivation. Naturally, activation builds faster when it is provided on several channels rather than just one. This provides an explanation for redundancy benefits that is different form the usual race model, which assumes independent processing on separate channels.

Although both separate activations and coactivation models can account for a redundancy gain they do not do so in the same way. Consider the fastest RTs in a distribution. The statistical facilitation (i.e., separate activations) model would hold that there should be more of these fastest times when there are more targets; this is why we get a redundancy benefit. However, on a coactivation model it may be the case that the fastest times in a multiple target condition are faster than the fastest times in any of the corresponding single target condition, because activation is summed across targets.

More formally and more generally, Miller has shown that the following relations hold for separate activation models. Assume here that there are two possible target locations, 1 and 2.

$$P(RT < t|S_1 \text{ and } S_2) = P(RT < t|S_1) + P(RT < t|S_2)$$

$$-P[(RT < t|S_1) \text{ and } (RT < t|S_2)]$$

The left side of the equation corresponds to the cumulative density function (CDF) of RT on redundant signal trials, and the first two terms on the right correspond to the CDFs for the two single target conditions. The final term reflects the correlation between the two activations.

From the preceding basic equation a prediction can be derived for all separate activation models:

$$P(RT < t|S_1 \text{ and } S_2) =< P(RT < t|S_1) + P(RT < t|S_2)$$

This is true because the rightmost term in the basic equation above is greater than or equal to zero.

What this last inequality says is that if a separate activations model holds, and we plot the CDF for redundant target trials and compare it to the sum of the single target CDFs the curve for redundant trials should be everywhere to the right of the curve representing the sum of the two individual stimuli. However, if coactivation occurs the curves might well cross. That is, at the short RT end of the distribution the curve for the redundant target trials might be to the left of the curve representing the sum of the two individual stimuli.

When coactivation is found this implies parallel processing. However, this is a very stringent test, and so the converse does not apply; a failure to find coactivation does not necessarily mean that processing is not parallel.

In several studies (e.g., Egeth & Mordkoff, in press) we have found coactivation with a conjunctively defined target (e.g., a red X, with the other stimuli being a red O and a green X). This is perhaps the strongest evidence yet found of spatially parallel processing of conjunctions.

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