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12 Using Repetition Detection to Define and Localize the Processes of Selective Attention

George Sperling, Stephen A. Wurst,
and Zhong-Lin Lu

12.1 INTRODUCTION

Overview

In our repetition-detection task, subjects search a rapid sequence of thirty frames for a stimulus that is repeated within four frames. Successful detection implies that a match occurs between an incoming item and a recent item retained in short-term visual repetition memory (STVRM).

We test selective attention to physical features in a single location within which successive items alternate in color, size, or spatial frequency. For example, in the size condition, large and small items strictly alternate, and subjects attend selectively to *small* (or to *large*) items. Selective attention to *small* facilitates detecting small-small repetitions and impairs detection of large-large repetitions (the benefit and cost of selective attention). In a control condition, the *large* items are replaced by blanks. The size of the attention benefit for small relative to the control performance gives the efficiency of attentional filtering relative to perfect optical filtering.

Whereas selective attention (relative to equal attention) facilitates homogeneous (e.g., small-small) repetition detections, it usually impairs heterogeneous detections (large-small or small-large). Comparisons of attention costs and benefits for homogeneous and for heterogeneous detections admit the following inferences: physical features are represented in STVRM; attentional filtering occurs before stimuli are recorded in STVRM; in some conditions, some subjects use strategies that encode the attention state of an item in STVRM.

Background: Early versus Late Selective Filtering

Theories of selective attention postulate that the human information processing system is limited in its capacity and that attention serves to select information to be processed from other, competing information (e.g., Broadbent 1958; Deutsch and Deutsch 1963; Norman 1968). Indeed, selective filtering of unattended information has been proposed as a mechanism in numerous visual processing tasks.

There is abundant evidence that selective attention can function as a mechanism to differentially filter information from different spatial locations (see reviews by Sperling and Dosher 1986; Sperling and Weichselgartner 1993). However, we find no convincing evidence that attention can function as a mechanism for selecting information on the basis of physical features when items containing different constellations of features occur at the same location. Rather, the data are consistent with a theory that asserts that stimulus features serve only to guide spatial attention. That is, whenever selection appears on the basis of the physical features of visual stimuli (such as color, spatial frequency content, size, etc.), these features serve to bring attention to a particular location, but the attentional filtering is on the basis of location rather than on the basis of feature. To test this theory, it is critical to present more information than can be successfully processed at a single location, and to observe whether, at this single location, attentional filtering is possible on the basis of physical features.

Selection from Streams

It is trivial to demonstrate that attentional filtering can occur within a given spatial location. Consider, for example, the following gedanken experiment. Subjects view a stream of alternating black and white digits on a gray background. Subjects are asked to compute the sum of the white digits and to ignore the black digits. Obviously, subjects can perform this task when the stream is slow enough, but this would not be profoundly revealing about selective attentional processes because we already know that selection can occur at a cognitive or a decision level of processing. The interesting questions about selective attention concern whether it can operate at an earlier sensory or perceptual level (reviewed in Sperling and Dosher 1986).

Search Procedures A useful technique for studying attentional selection at a single location is to present a rapid stream of items at a location too rapidly to permit all items to be processed perfectly. Attentional selection can then be used to determine which items are processed. There are a number of tasks that involve items that are presented in a rapid visual stream at a single location. For example, Sperling et al. (1971) studied rapid visual search as a function of the number of locations in which streams of items were presented. However, the problem with search experiments is that, so far, no procedure has been developed to determine whether attentional selection (i.e., rejection of nontarget items) occurs at the perceptual or at the decision level of processing. Indeed, recent theories of selective filtering (Cave and Wolfe 1990; Duncan and Humphreys 1989; Pavel 1991; Wright and Main 1991; cf. Hoffman 1979) propose various cue-weighting algorithms to determine the sequence of attentional selections in visual search. Such weighting processes are typical of decision processes, although the algorithms themselves are neutral with regard to whether they operate at a perceptual or a decision level of processing.

Feature-based Partial Reports from Streams Another task involving a stream is the selective recall of items according to their physical characteristics. The procedure involves the selection of items from a rapid stream according to whether or not the target items have a distinguishing characteristic such as a ring around them, or whether they are brighter than their neighbors. Subjects can extract single target items from a rapid stream (Intraub 1985; Weichselgartner and Sperling 1987), or even a short sequence of four targets (Weichselgartner 1984). In fact, such experiments are partial report experiments in which the many items (from among which a few are selected for a partial report) are arrayed in time rather than in space as in the more usual procedure (Sperling 1960).

Feature-based Partial Reports from Spatial Arrays In spatial arrays, subjects can select items for partial report that have a ring around them (Averbach and Sperling 1961) or items that merely are pointed at by a short bar marker—a minimal feature for selection. When subjects are required to report only items of a particular color from briefly exposed letter matrices, these partial reports are not much better than whole reports (von Wright 1968). Similarly, when subjects are required to report only digits from mixed arrays of letters and digits, subjects do not report more digits than when they must report both letters and digits (e.g., Sperling 1960). Both of these studies required subjects to extract both item-identity and location information from briefly exposed arrays. When subjects are required only to report the item identities and not locations, partial reports according to feature easily surpass whole reports (e.g., selecting solid from outline characters; Merikle 1980). Thus, with comparable response requirements, feature-cued partial reports are comparably successful in temporal streams and in spatial arrays.

Partial Reports according to Spatial or Purely Temporal (versus Featural) Cues Originally, partial reports were studied in spatial arrays, and the selection cue designated one of several rows of characters—purely spatial selection (e.g., Sperling 1960, 1963). With spatial cues, there is a large and consistent partial-report advantage. When subjects must use a temporal cue to make a partial-report selection of four items from a rapid temporal stream, item selection appears to be based on a temporal window of attention (Sperling and Reeves 1980; Reeves and Sperling 1986; Weichselgartner and Sperling 1987). The subject's temporal window for selection from temporal streams is perfectly analogous to the spatial window for selection from spatial arrays (e.g., LaBerge and Brown 1989).

The Locus of Feature-based Attentional Selection Partial-report paradigms primarily focus on the process whereby information is selected for inclusion in short-term memory. That feature-based attentional selection of information for partial reports can occur in streams and in arrays merely places the level of attentional selection below the level of short-term memory. This constraint is unremarkable. Therefore, it is search tasks that seem most often to have been called forth to resolve the issue of early versus late selection on the basis of physical features (recent examples include Nakayama and Silverman 1986; Neisser 1967; Treisman 1977; Treisman 1986; Treisman and Gelade 1980; see Folk and Egeth 1989 for a review). Closely related issues are automatic versus controlled processing (Shiffrin and Schneider 1977), speeded classification (e.g., Felfoldy and Garner 1971; Garner 1978) and auditory selective attention (Swets 1984). The ambiguity of current search theories concerning the level of attentional selection was noted above. This is not the place for a review and critique of the many other approaches to these problems in the visual and auditory domains. Instead, we offer new variations of a repetition-detection task and new analyses that are particularly well suited to defining the locus of feature-based attentional selection (i.e.. perceptual filtering according to physical properties).

Repetition-Detection Paradigm

The repetition-detection paradigm (Kaufman 1978; Wurst 1989; Sperling and Kaufman 1991) seems particularly well suited for the study of attentional selection based on physical features. In this paradigm (fig. 12.1), a stream of thirty digits is presented rapidly (typically, 9.1 digits per sec). Within this stream, every digit is repeated three times, but only one digit is repeated within four sequence positions (lag 4 or less); all other digits are repeated with lags of nine or more. The subject is instructed to detect the recently repeated digit. Successful performance of this task obviously depends on the subject's ability to match incoming digits with previously presented digits in memory. Because all digits are repeated exactly three times within a list, only memory

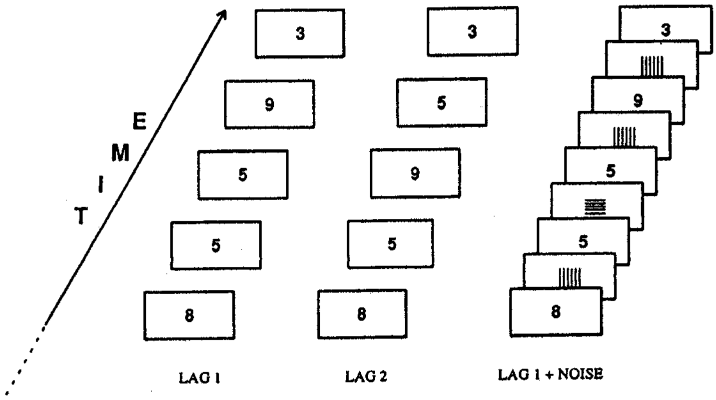


Figure 12.1 The repetition-detection paradigm. The leftmost sequence (lag 1) represents five consecutive frames from the middle of a longer sequence of frames. The target repetition is the digit 5. The middle sequence illustrates repetition of the digit 5 with lag 2. The rightmost sequence illustrates Kaufman's (1978) noise condition with lag 1. A grid of randomly chosen vertical or horizontal lines is interposed between each digit frame; repetition-detection performance was unimpaired.

that discriminates short-lag repetitions from long-lag repetitions is useful for performing this task.

In previous research (Kaufman 1978; Sperling and Kaufman 1991), it was found that, at lag 1, repetition detection was typically better than 80 percent correct, and that by lag 4 it had dropped below 30 or 40 percent. Adding a noise field between successive frames (fig. 12.1) did not impair performance, even when the noise field was so intense that, if it were simultaneous with digit presentations, it would have rendered them illegible. This immunity to visual masking suggests a central memory locus for short-term visual repetition memory (STVRM), even at lag 1.

In another adaptation of the task (Kaufman 1978; Sperling and Kaufman 1991), it was found that using nonsense shapes as stimuli instead of digits yielded equivalent results. This suggests that STVRM is visual rather than verbal or semantic.

Wurst (1989) used dicoptic presentations to demonstrate that the locus of short-term visual repetition memory (STVRM) was after the locus of binocular combination. A particularly interesting finding in Wurst's dicoptic viewing procedure was that one eye was given priority over the other eye. Thus, a filtering of items by the eye of presentation may have been occurring even though items were presented alternately (never simultaneously) to the two eyes and though, in control conditions, monocular performance was the same for both eyes. The present study was undertaken to determine whether selection could occur by varying stimulus attributes other than the eye of presentation.

Plan of the Experiments

To investigate the role of attention in the short-term visual repetition memory task, as in the previous studies, digits are presented in the same spatial location while being viewed binocularly. Two levels of a dimension are employed (e.g., large and small sizes of digits), and digits alternate between the levels. We will call a level of a dimension a *feature*. For example, *small* and *large* are features within the size dimension. In this study, five stimulus dimensions that have typically been employed in attention research (e.g., Nakayama and Silverman 1986; Treisman 1982; Sagi 1988)—size, angular orientation, spatial bandpass filtering, contrast polarity (black-on-gray vs. white-on-gray), and color—are examined separately. Additionally, we examine one feature pair (small black vs. large white). Digits with a different feature (e.g., large and small size) are alternated at the same location. We determine the ability of subjects to attend selectively to items with one feature (or feature pair) while ignoring items with the other feature (or feature pair).

12.2 METHOD

Experiment 1 examines five individual stimulus dimensions—orientation, size, contrast polarity, color, and spatial bandpass filtering—and one dimensional pair (small black vs. large white). Experiment 2 investigates three sets of stimulus characters and will be described more fully below.

A stimulus sequence consists of thirty consecutive digits. A position in the sequence is called a *frame*; thus we say the *i*th digit occurs in the *i*th frame. Stimuli in a sequence alternately exhibit one level A of a dimension on odd-numbered frames, and the other level B of the same dimension on even-numbered frames. We call such as sequence $\frac{1}{2}A + \frac{1}{2}B$. If subjects were completely successful in selectively filtering out unattended B stimuli on the even-numbered frames, detection of the repetitions of the attended-to-feature in a $\frac{1}{2}A + \frac{1}{2}B$ sequence would be similar to a control condition ($\frac{1}{2}A$) in which the even-numbered frames were simply blank. If the selection were totally unsuccessful, for example, if the features were indiscriminable, then the alternating feature sequence should be as difficult as a same-feature sequence (A). Consider performance in the two control conditions $\frac{1}{2}A$ and A. The point between these two performances where performance with $\frac{1}{2}A + \frac{1}{2}B$ falls indicates the success of attentional filtering. This is the broad plan of the experiments. Additional complications will become apparent as the story unfolds.

Stimulus Generation

Frames The repetition-detection procedure (Kaufman 1978; Sperling and Kaufman 1991), was used in this experiment. Each trial consisted of a stream of thirty digits displayed on a video monitor. A digit was painted three times (three refreshes), followed by six refreshes of a blank, gray screen, all at sixty refreshes per second. The sequence of nine refreshes (digit plus subsequent blank screen) is called a *frame*. The frame duration is 150 msec; equivalently, the digit-to-digit stimulus onset asynchrony (SOA) is 150 msec. A digit sequence was composed of thirty frames: the ten digits, each presented three times.

Lag To distinguish the different types of repetitions that occur, we use the term *lag*. When a digit occurs in frame i of the sequence, and then again in frame j, $1 \leq i < j \leq 30$, the digit is defined as being repeated with lag $j - i$ (see fig. 12.1). Only the target digit was repeated within a lag of 4 or less; all other repetitions of the digits were separated by eight or more intervening digits (lag ≥ 9). To generate a stimulus sequence, the first digit is chosen randomly. Subsequently, at any point in sequence generation, the requirement that no digit be repeated with lag ≤ 8 restricts the number of digits eligible to be chosen. At each point (except the critical repetition), the new digit was chosen with equal probability from among the eligible digits. The critical repetition was embedded at a random location in the sequence, so that (1) the first member of the repetition pair occurred between sequence positions 11 and 20, and (2) all other sequence constraints remained satisfied. Each sequence was generated by a new random draw.

Figure 12.2a shows a typical sequence of thirty digits. Figure 12.2b shows the expected distribution of lags in such a sequence. A single lag of 1, 2, 3, or

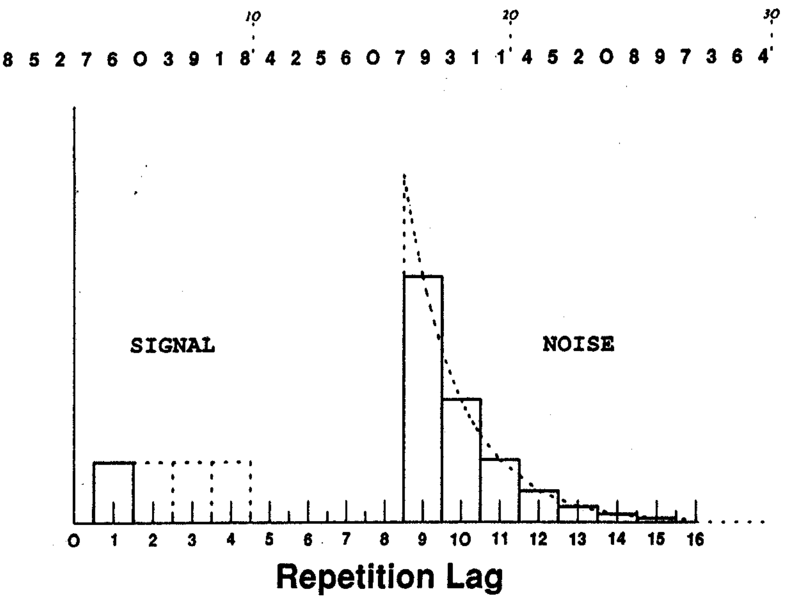


Figure 12.2 *Top:* A stimulus sequence in the repetition-detection experiment. *Bottom:* The expected frequency distribution of signal (target) and noise repetitions. Signal indicates that, on each trial, there is exactly one signal repetition; its lag is either 1, 2, 3, or 4. Nontarget digits are constrained to repeat only with lags of 9 or more (noise repetitions). The numbers 10 and 20 (top) demark the middle ten positions of the sequence within which the initial element of the target repetition is constrained to occur. These two constraints determine the expected frequency distribution of noise repetitions, indicated as NOISE.

4 represents the to-be-detected repetition—the signal. All the other repetitions have lag ≥ 9 and represent the noise. The distribution of noise lags is approximately exponential; it is truncated because repetition lags greater than 21 are impossible. While the actual noise distribution of lags is well defined, the *effective* noise distribution depends somewhat on how precisely, in such a rapid sequence, subjects can use their knowledge of constraints on the frames in which repeated pairs are permitted to occur (see below).

Procedures Subjects were instructed to detect the repetition of lag 4 or less, and not to respond to any of the other stimuli. No masking stimuli were interleaved between the digits. All digits were presented in the same spatial location, centered on the CRT screen.

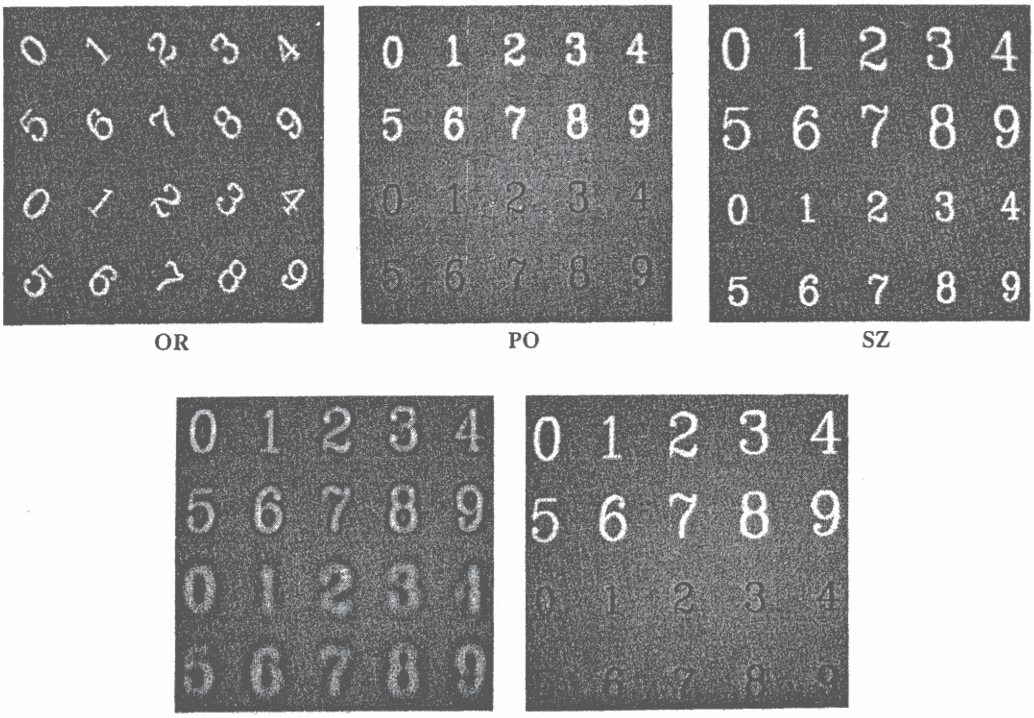
A trial began with a centrally located fixation square. When the subject was ready to begin the trial, the subject pressed any key on the computer keyboard. After a repetition was detected, the subject pressed the return key as quickly as possible. After the end of the sequence, a message was presented on the monitor that cued the subject to enter the repeated digit and to enter a confidence rating between 0 (very low confidence that the response was the repetition) and 4 (very high confidence that the response was the correct repetition). The actual repeated digit was then presented on the screen to give the subject complete accuracy feedback information. A message to press the Return key was displayed, following which, the fixation square for the next trial appeared.

Stimulus Sets

Subjects viewed all stimuli at a distance of 93 cm. The square fixation box was 2.46 × 2.46 degree visual angle. The digits 0 to 9 were used in the Times Roman font. The background of all displays and blank intervals was set at 50 cd/m^2. Unless otherwise specified, digits were white on gray, with a digit height of 0.74 degree.

Six stimulus dimensions were investigated separately in the experiments. There were two levels (feature values) for each of the six dimensions. The stimulus sets are shown in figure 12.3. The six dimensions (and the two feature values of each, *A* and *B*, respectively) were

1. *Size* (large, 0.74 degree visual angle versus small, 0.49 degree visual angle).
2. *Orientation* (slanted 45 degrees up-to-the-left versus slanted 45 degrees right).



OR

PO

SZ

BP

PS

Figure 12.3 Stimuli used in the experiments. In each panel, the top ten digits are the type *A* stimulus of the indicated dimensions (orientation, polarity, size, bandpass, polarity and size). The bottom ten digits are the type *B* stimuli. Color (not shown) is similar to PO.

3. *Contrast Polarity* (white digits on gray background versus black digits on gray). The luminance level of the white digits was 101.50 cd/m^2, and the luminance level of the black digits was 0.40 cd/m^2 against a background of 50 cd/m^2.

4. *Color* (red digits on gray background vs. green digits on gray). Both red and green digits were 68 cd/m^2; saturation was chosen such that red and green were perceived as "equally different" from the background of 50 cd/m^2.

5. *Bandpass Filter* (high spatial bandpass vs. low spatial bandpass). The mean luminance level for all bandpass-filtered stimuli was 50 cd/m^2. The high bandpass digits had a mean two-dimensional frequency of 5.77 cycles per letter height, and the low bandpass digits had a frequency of 2.92 cycles per letter height. (See Parish and Sperling 1991 for a description of the filters.)

6. *Polarity and Size* Large white digits represented feature type *A*; small black digits were type *B*. All were presented against the gray background. (Large, small, light, dark, gray were as defined above.)

Blocks of Trials

Figure 12.4 illustrates the design of experimental and control stimulus sequences and presents examples. A block of trials contained only one of the six stimulus transformations (fig. 12.3). The experimental blocks all were of type ($\frac{1}{2}A + \frac{1}{2}B$) in which streams of strictly alternating *A*, *B* stimulus features were presented. There were three kinds of experimental blocks for a given transformation that differed in the attentional conditions: attend to *A*, equal attention, attend to *B*). In addition to experimental blocks, which consisted of sequences that alternated two feature values (*A* and *B*), there were control blocks, which consisted of digits having the same feature value throughout.

Experimental blocks contained 100 trials, and control blocks contained 150 trials. Every subject ran at least four blocks in every condition (2400 trials per transformation). Each of the trials was classified according to lag 1, 2, 3, or 4. In the experimental ($\frac{1}{2}A + \frac{1}{2}B$) blocks, trials were classified according to whether the repetition pair was *aa*, *ab*, *ba*, or *bb*. We use *A* and *B* to denote features or streams that contain the features (e.g., A = large and B = small). We use *a*, *b*, respectively, to denote target digits—members of the repetition pair—that contain features *A* and *B*, respectively.

Attention Conditions

The three experimental blocks are distinguished by the attentional instructions, the probability of the different types of repetitions presented, and the payoffs for correct responses. For the Attend-*A* experimental block the subject was instructed to devote 80 percent of attention to feature *A* (e.g., large) and 20 percent to feature *B* (e.g., small); for the Attend-*B* experimental block, the subject was instructed to devote 80 percent of attention to feature *B* (e.g., small) and 20 percent to feature *A* (e.g., large). In equal-attention experimental

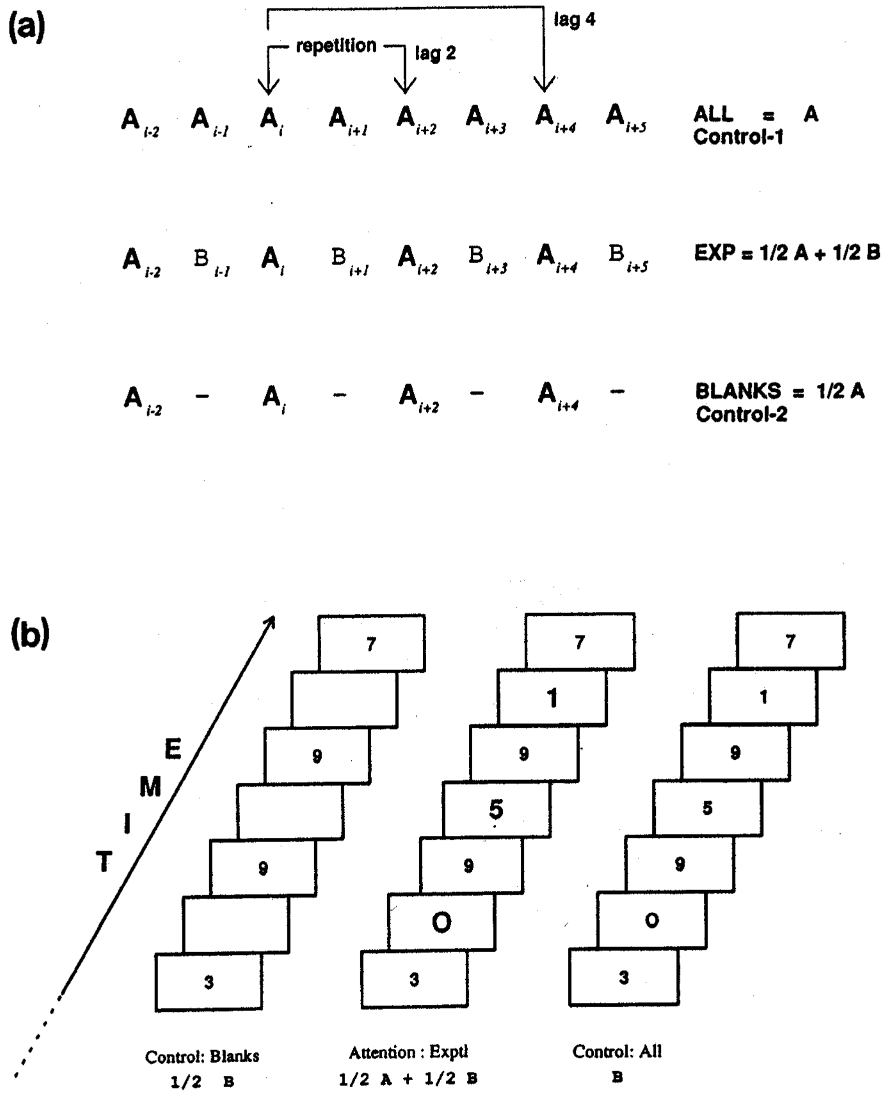


Figure 12.4 Experimental and control presentation sequences used to estimate the effectiveness of attentional filtering. (a) The middle row indicates the experimental condition, an alternating sequence of type *A* and type *B* stimuli, designated as $\frac{1}{2}A + \frac{1}{2}B$. If the subject could not discriminate the features that distinguished the type *A* and type *B* stimuli, the subject would perform equivalently in the $\frac{1}{2}A + \frac{1}{2}B$ and in the All control, which consists entirely of *A* stimuli, designated simply as *A*. On the other hand, if the subject were able to perfectly ignore the unattended-*B* feature in the $\frac{1}{2}A + \frac{1}{2}B$ stream, experimental performance would be equivalent to the Blanks control, designated as $\frac{1}{2}A$. This would be true for repetitions at lag 2 and at lag 4 (indicated above). (b) Graphical illustration of the three types of displays. The dimension is size. Type *A* stimuli are large, type *B* are small; the example illustrates *bb* targets.

Table 12.1 Probability of Each Condition within Each Block of Trials

Blocks of Alternating-Feature Sequences (*AB*)

	Attend-*A*		Attend-*B*		Attend-equal	
Target =	A	B	A	B	A	B
Lag 1*	.05	.05	.05	.05	.07	.07
Lag 2	.35	.05	.05	.35	.18	.18
Lag 3*	.05	.05	.05	.05	.07	.07
Lag 4	.35	.05	.05	.35	.18	.18

Blocks of Single-Feature Sequences

	Feature *A*		Feature *B*	
Stim. =	AA	A−	BB	B−
Lag 1	.167	—	.167	—
Lag 2	.167	.167	.167	.167
Lag 3	.167	—	.167	—
Lag 4	.167	.167	.167	.167

*Mixed-feature repetition pairs; "Target" indicates the feature of the first element of the pair.

blocks, the subject was instructed to devote 50 percent of attention to feature *A* and 50 percent to feature *B*. The probabilities of different trial types for the Attend-*A*, Attend-*B*, and Attend-equal blocks are shown in table 12.1. Note that when attending to feature *A*, 70 percent of the trials in the selective attention blocks are pure (*aa*) repetitions (35 percent at lag 2, 35 percent at lag 4). The remaining trials consist of mixed repetitions at lags 1 and 3, (*ab*) 10 percent, (*ba*) 10 percent, and of pure unattended-feature repetitions at lags 2 and 4, (*bb*) 10 percent. The converse holds when attending to feature *B*.

The attention instructions served only to define the initial conditions for the subjects. The steady-state behavior of subjects was controlled by carefully defined rewards to enforce the attention conditions. For every stimulus repetition in the attended-to stream that the subject detected correctly (that is, an *aa* or *bb* pair), the subject received five points. The subject received only one point for detecting repetitions in the unattended stream, and zero points for for the heterogeneous *ab* and *ba* repetitions. The paid subjects were paid 1 cent per point (in addition to their usual hourly wage for participation). The maximum expected payoff per trial for detecting targets with the attended feature is their probability of occurrence (0.7, table 12.1) times their value (5 cents), a net of 3.5 cents. The maximum expected earnings from detecting targets with the unattended feature is 0.1 × 1 cent = 0.1 cent. Thus, the expected value of detecting repetitions with the attended-to feature was thirty-five times greater than the value of unattended-feature repetitions. The 35 : 1 attended/unattended ratio of maximum possible earnings exerted a potent control over attention, although some of the effects of attention were unanticipated.

100 Percent–0 Percent Attention Conditions Even the extreme divided attention conditions (nominally 80 percent–20 percent) involve divided attention because, when the subject notices repetitions involving the unattended feature, they are reported. Why not include experimental conditions in which the subjects are told to give 100 percent (rather than 80 percent) of their attention to the attended feature, and to give 0 percent (rather than 20 percent) to the unattended feature, and are paid only for detecting attended-feature repetitions? In previous research, Sperling and Melchner (1978a, 1978b) compared 100 percent–0 percent attention to a range of divided attention conditions similar to the nominal 80 percent–20 percent range used here. Sperling and Melchner's attentional manipulation involved only instructions; in contrast to the present study, their instructions were unenhanced by differential probabilities of occurrence of or by differential rewards for detecting attended targets. Nevertheless, in one-third of their cases, Sperling and Melchner's (1978b) divided-attention conditions spanned a range of performances that was fully as great as the extremes of the 100 percent–0 percent control conditions, and their remaining divided-attention cases spanned most of the 100 percent–0 percent performance range. Thus, while 100 percent–0 percent conditions might (or might not) slightly expand the range of performances observed here, the added conditions would not be expected to produce any qualitatively different data.

Controls ($A, B, \frac{1}{2}A, \frac{1}{2}B$) Control blocks were run for each feature, as indicated in figure 12.4 and in table 12.1. In the control-All trials (A and B), all thirty digits have the same feature value, and lags 1, 2, 3, and 4 occur equally often. Control-All trials were interleaved with control-Blanks trials ($\frac{1}{2}A$ and $\frac{1}{2}B$) in which every other digit in the sequence was replaced by enough blank frames to permit the remaining digits to retain their precise temporal positions in the sequence. Therefore, for control-Blanks, only fifteen digits were presented, and repetitions only occurred at what, in the All sequence, would have been called lags 2 and 4 (since blanks occurred at lags 1 and 3). As indicated in table 12.1, the six control conditions with feature A (or feature B) had an equal probability of occurring (i.e., twenty-five trials for each condition in the control blocks).

Altogether, there were thirty-six different kinds of trials for each of the six stimulus transformations (fig. 12.3). There were twenty-four experimental conditions: 4 lags (1, 2, 3, 4) × 3 attentional instructions (80%, 50%, 20%) × two kinds of targets (*aa*, *bb* at lags 2, 4; *ab*, *ba* at lags 1, 3). And there were twelve control conditions: control-All contained 4 lags (1, 2, 3, 4) × 2 features (A, B), whereas control-Blanks contained 2 lags (2, 4) × 2 features ($\frac{1}{2}A, \frac{1}{2}B$).

Apparatus

A desktop computer (an IBM-compatible AT personal computer) was used to present stimuli and collect subjects' responses. Stimuli were created with HIPS image-processing software (Landy, Cohen, and Sperling 1984a, b) and displayed using a software package (Runtime Library for Psychology Experiments 1988) designed to drive an AT-Vista Videographics Adapter that produced black-and-white and color images on a NEC Multisync-Plus monitor (with horizontal resolution of 960 dots, vertical resolution of 720 lines, and short persistence phosphors).

Subjects

Two female and three male New York University graduate students and staff with normal or corrected-to-normal vision participated in this research. Three of these subjects were paid for their participation, and two were experimenters. All subjects were well practiced on the repetition-detection procedure before the formal experiments began.

Experiment 2

In the procedure described so far, there are twenty repetitions (three occurrences of each digit) with only the target repetition having a lag of 1, 2, 3 or 4 and all the others having lags of 9 or greater. Experiment 2 was designed to investigate whether this aspect of the procedure was critical to the results. Three character sets were created.

1. Ten digits (as used in experiment 1).

2. Twenty-nine unique characters consisting of the ten digits plus nineteen letters. (The letters B, I, O, Q, S, V and Z were eliminated because of their similarity to digits or other letters.) When using this character set, only the critical item is repeated.

3. A set of ten randomly chosen characters from among the twenty-nine, with a new random selection being made on each trial. Sequences were composed as for the digit stream.

The physical characteristics of the stimuli were the same as in the white-on-gray transformation. On each trial, the character set (1, 2, 3) and the lag (1, 2, 3, 4) were chosen randomly and independently. There were six sessions of 100 trials for subject SW, twelve sessions for subject ZL.

12.3 RESULTS AND DISCUSSION

Experiment 2: Different Character Sets

Figure 12.5 shows the data of experiment 2. There is a typical drop of performance with increasing lag but absolutely no indication of any systematic difference in the results for the three different character sets. Most theories of memory would suggest that, by eliminating the noise repetitions, the twenty-nine-element set would greatly improve performance. However, this effect is insignificant. The robust invariance of the data despite variations in the

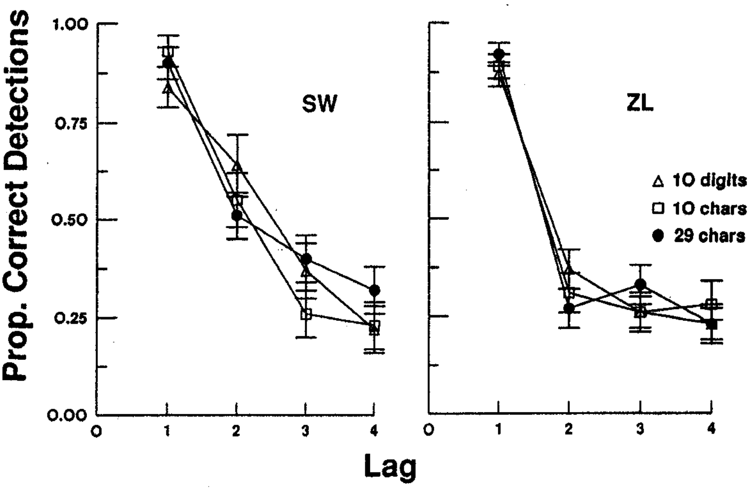


Figure 12.5 Results of variations in the character set (experiment 2). Data are shown for two subjects (SW, ZL). Lag is plotted on the abscissa, and proportion of correct detections on the ordinate. All stimulus streams contained thirty items; the curve parameter indicates the character set from which they were chosen. Open triangles—ten digits; filled circles—twenty nine characters (ten digits plus nineteen letters); open squares—a new set of ten characters chosen randomly on each trial from among the twenty nine.

nature and number of repetitions suggests that the immediate temporal environment of a repetition is the main determiner of whether or not it will be detected, and that variations in the more distant environment of a repetition are unimportant.

Experiment 1: Phenomena Illustrated with Selected Data

In the main experiment, there are thirty-six data points for each of the six types of stimuli. Therefore, presentation of the results is quite complex. We use three types of graphs. The first shows the attention conditions relative to the controls; the second shows attention-operating characteristics; and the third shows all thirty-six conditions on a single graph. We also table the benefits conferred by feature interleaving and by attentional manipulations.

Figures 12.6a, b, c show data from subject JW viewing the contrast polarity stimuli. Figure 12.6a shows detections of *aa* (white-white) repetitions in three stimulus contexts: two control stimuli ($\frac{1}{2}A$ and A, white-on-gray stimuli) and the experimental stimuli ($\frac{1}{2}A + \frac{1}{2}B$, alternating white and black stimuli). Consider first the control conditions $\frac{1}{2}A$ and A. The condition $\frac{1}{2}A$ represents a plausible upper bound on the attention conditions because it corresponds to what would be expected if the subject succeeded in ignoring B stimuli completely. The control A represents a plausible lower bound in which the B stimuli are indiscriminable from A stimuli. The projection of the diagonal line of figure 12.6a on the vertical axis (from 0.60 to 1.00) indicates the plausible bounds on the range of attention effects.

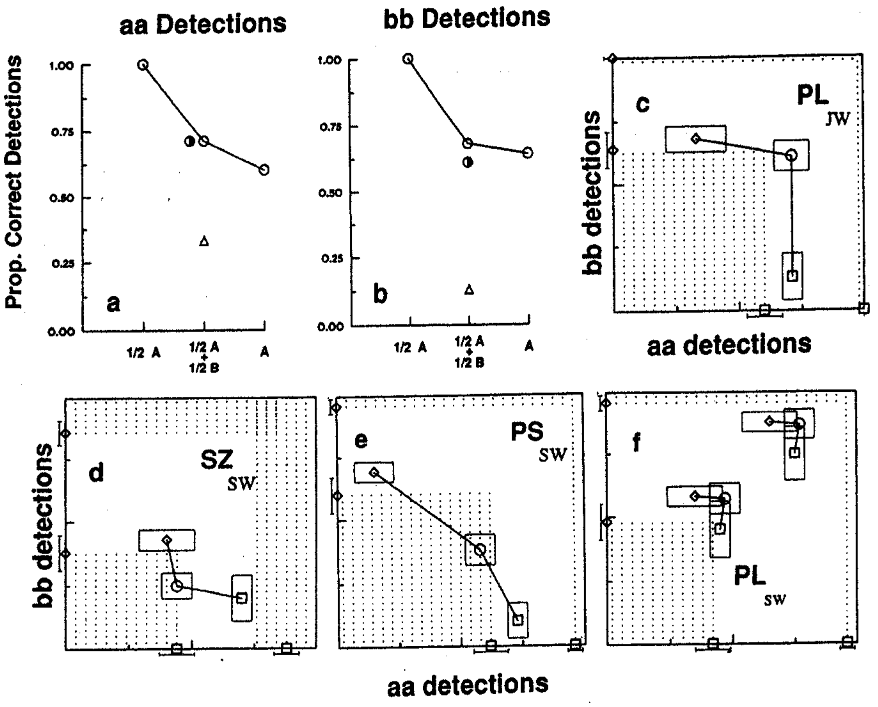


Figure 12.6 Illustrative results. (a, b, c) Polarity stimuli at lag 2 for subject JW. *A* = white-on-gray, *B* = black-on-gray. (a) The proportion correct in detecting *aa* (white-white) repetitions. Abscissa indicates the three types of stimuli (see text). The $\frac{1}{2}A + \frac{1}{2}B$ stimuli serve three attention conditions: the open circle indicates Attend-*A*, and it is connected by lines to the control conditions (which involve only *aa* repetitions); the half-filled point represents equal attention; the triangle indicates detecting *aa* while attending *B*. (b) Data for detecting type *bb* (black-black) repetitions. The open circle represents Attend-*B*; the half-filled point represents equal attention; the triangle indicates detecting *bb* while attending *A*. (c) Attention-operating characteristic (AOC) derived from the data of panels (a) and (b). The abscissa and ordinate both range from 0 to 1.0 and represent the proportions of correct *aa* and *bb* detections. The inner shaded area indicates performance worse than the corresponding *All* controls (*A*, *B*) for both *aa* and *bb* detections. The concave-down curve is the AOC derived from the $\frac{1}{2}A + \frac{1}{2}B$ stimulus with the points representing, from left-to-right, Attend-*A*, equal attention, and Attend-*B*. The error bars indicate one standard error of the mean; the relative sizes of the errors derive from the inverse square root of the number of observations. The concave-down curve of this AOC corresponds to costs but no benefits from selective attention. (d, e, f) Examples of different types of performance. (d) AOC for subject SW at lag 2 with size stimuli (*A* = large; type *B* = small). The concave-up shape of the AOC indicates benefits from selective attention without costs. The outer shaded area indicates performance better than a *Blanks* control ($\frac{1}{2}A + \frac{1}{2}B$) for one or both of the two types of targets (*aa*, *bb*). (e) AOC for subject SW at lag 2 with polarity-and-size stimuli (*A* = large-white, *B* = small-black). The AOC with slope ≈ -1 indicates symmetrical trade-offs of costs and benefits of selective attention. (f) Two AOCs are plotted: the lower-left AOC is the AOC for subject SW at lag 2 with polarity stimuli (*A* = white, *B* = black). This real AOC is "enhanced" by adding 0.3 to each coordinate to produce the "enhanced" AOC at the upper right. The real AOC indicates a small stimulus differentiation benefit; the "enhanced" AOC indicates a large benefit; attention effects are identical for both AOCs.

In the experimental conditions, $\frac{1}{2}A + \frac{1}{2}B$, full attention to feature A while ignoring B is represented by the middle point on the diagonal line of figure 12.6a. Full attention to A shows a benefit relative to the control-All-A condition but not nearly as great a benefit as occurs when the B stimuli are replaced with blanks.

Two unconnected data points are shown in figure 12.6a. The half-shaded point adjacent to the full-attention point in figure 12.6a indicates equal attention. Equal attention in an alternating $\frac{1}{2}A + \frac{1}{2}B$ stream yields better performance than in the All-A stream because mixing two features in the stream (instead of only one) makes the stimuli more discriminable. Attention to B stimuli leads to poor performance on *aa* repetitions (0.25), and this is indicated by the triangle in figure 12.6a.

We expect good symmetry between features A and B (white-on-gray, black-on-gray). Indeed, figure 12.6b, generated for detections of *bb* repetitions, is basically similar to figure 12.6a.

Generating Attention-Operating Characteristics (AOCs) The $\frac{1}{2}A + \frac{1}{2}B$ points in figures 12.6a and 12.6b generate the AOC (Kinchla 1980; Sperling and Melchner 1978b) of figure 12.6c. The lower-right square of figure 12.6c indicates joint performance on *aa* and *bb* repetitions when attention is directed to A. The rectangle around the square indicates one standard error of the mean in each dimension. The rectangle is extended in the B dimension because, in the Attend-A condition, there are seven times more *aa* repetition trials than *bb* trials, and this increases the standard error of *bb* detections relative to *aa*. The circle in figure 12.6c indicates equal-attention performance, and the diamond at the upper-left end of the AOC indicates Attend-B performance. Based on the data of figures 12.6a and 12.6b, the shape of the AOC is concave down, the limbs forming almost a right angle. The severe concave-down shape indicates that, relative to equal attention, selective attention yields negligible benefits but significant losses.

Additionally, figure 12.6c indicates a shaded area that represents excluded performances. Regardless of the state of attention, we expect performance in $\frac{1}{2}A + \frac{1}{2}B$ to equal or exceed performance in the All-A and All-B control conditions. This constraint excludes data from the lower-left rectangle of the AOC graph.

Figure 12.6d indicates an AOC derived from subject SW viewing the *size* stimuli. Here, the AOC is concave up. It indicates that, relative to equal attention, paying selective attention to large (A) stimuli improves detection of *aa* repetitions with only an insignificant loss of detectability of *bb* repetitions. Similarly, attending to small (B) stimuli significantly improves detection of *bb* repetitions but does not significantly penalize *aa* detections. A right-angle concave-up shape of AOC indicates benefits of selective attention with no costs.

Figure 12.6d illustrates a second shaded region that was absent in figure 12.6c because of that subject's perfect performance in the control conditions. Regardless of the state of attention, we expect the subject to perform worse in any experimental $\frac{1}{2}A + \frac{1}{2}B$ condition than in the corresponding $\frac{1}{2}A$ or $\frac{1}{2}B$ control condition. This excludes data from the shaded area in the outer rim of the AOC graph.

The pure costs and pure benefits indicated by the AOCs of figures 12.6c and 12.6d are somewhat unusual. Figure 12.6e (subject SW, polarity-and-size stimuli) illustrates a more typical AOC. The slope of -1 suggests a symmetrical trade-off between the costs and benefits of selective attention. The most common interpretation of linear AOCs is that the subject can perform only one task or the other, and that the equal-attention point represents a mixture of these two strategies (Sperling and Dosher 1986; Sperling and Melchner 1978a). Such a switching strategy could cause the AOC to traverse the excluded region and influence the equal-attention point to lie within it.

AOCs for the Data

Figure 12.7 shows all the AOCs from the experiments. The twenty-eight AOCs represent six stimulus transformations, each with lags 2 and 4. There are two subjects for each of the first four conditions and three subjects for the two remaining. Overall, the AOCs look similar to those illustrated in figure 12.6. Performance is consistently better for lag 2 than for lag 4.

Several AOCs show pure costs: for example, polarity (SW, JW, lag 2), and size (JW, lag 2), and many AOCs have a purely vertical or horizontal leg to indicate that one of the two selective-attention conditions results in pure costs. All in all, there are very few examples of AOCs that can be interpreted as yielding a continuum of trade-offs. We defer further discussion of these graphs until we consider the full range of data and additional summary statistics.

Consolidated Graphs of All Experimental and Control Conditions

Each panel of figure 12.8 shows mean data for each of the thirty-six kinds of repetition detections for one subject and one set of features. Except for variances and tests of significance, these graphs represent the entire data of the experiments. The plan of figure 12.8 is to indicate the data of control conditions by two sets of connected lines that form upper and lower reference bounds for four clusters of points that represent the data of the experimental conditions. We begin by making some general observations.

The Effects of Lag and SOA The effects of lag on repetition-detection performance are indicated in figure 12.8 by the sloping connecting lines that indicate performance in the control-All-*A* and All-*B* conditions. Performance with the control-All stimuli is at or above 75 percent at lag 1 for nearly all subjects and types of stimulus transformation. There are clear individual differences. For example, in the polarity-and-size conditions, subject ZL performs better at lag 1 than does subject SW, although SW had much more practice. These lag data are completely consistent with earlier observations (Kaufman 1978).

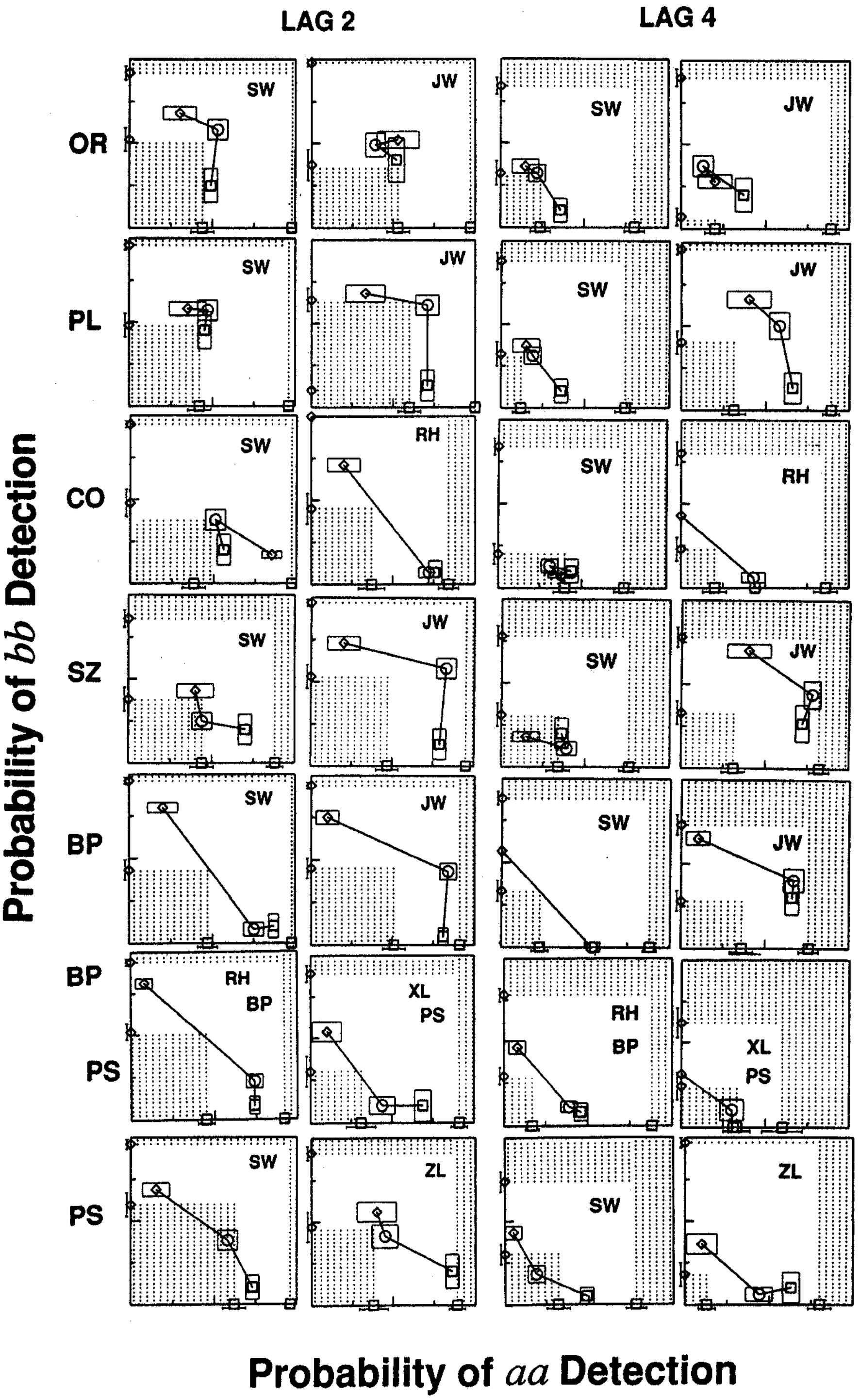


Figure 12.7 Attention-Operating Characteristics (AOC) for all subjects, stimulus transformations, and lags. Rows indicate different stimulus transformations (see figure 12.3) except row 6, which is shared by two different stimuli. The abscissa is the probability of detecting *aa* targets, the ordinate indicates *bb* detections. Coordinates range from 0 to 1.0. Symbols repre-

The effect of SOA is derived from the sloping lines labeled $A/2$ that represent data for the control-Blanks conditions ($\frac{1}{2}A$, $\frac{1}{2}B$), and which appear above lags 2 and 4. Performance in control-Blanks is better than the corresponding control-All (A, B) data. Alternatively, the control-Blanks conditions with lags 2 and 4 might be described as lags 1 and 2 of a stream with a doubled SOA (stimulus onset asynchrony—the time from the onset of one digit to the next). However, the control-Blanks is not quite equivalent to a slower sequence because it has only fifteen instead of the thirty items that would be produced by simply slowing the stream. The combined manipulation of slowing and shortening the sequence produces (except for ceiling effects) better performance for the control-Blanks than the comparable control-All conditions: control-Blanks, lag 2, surpasses control-All, lag 1, and control-Blanks, lag 4, surpasses control-All, lag 2.

The obvious interpretation of these data is that the main cause of the decline of performance with lag is retroactive interference (versus passive decay). Increasing the SOA increases the amount of time that the items must be retained but actually improves performance. (We know this also from unpublished observations in our laboratory in which sequence length was controlled.)

Repetition Blindness The improvement of detection with shorter lags is different from another phenomenon discovered recently by using superficially similar procedures. "Repetition blindness" (Kanwisher 1987) is the reduced ability of subjects to report both occurrences of a repeated word embedded in a rapid sequence (approximately 4 to 9 per second) relative to the reportability of two independent words. In contrast to the present research, reportability of both occurrences of the word increases with increasing lag. There are several differences between our repetition-detection procedure and the procedure Kanwisher used. Repeated items are discriminated from unrepeated items in Kanwisher's studies rather than from other equally-often-repeated items, as in ours. However, the equivalence of the twenty-nine-element character set of experiment 2 (in which all noncritical repetitions were eliminated) to the other character sets shows that multiple repetitions are not the cause of the difference in results.

The repetition-blindness paradigm tests the tendency of subjects to report both occurrences of repeated items rather than their ability to discriminate repeated from unrepeated items. Moreover, repetition-blindness experiments typically have used linguistic stimuli (words) in the stimulus sequence, in some instances varying the context in which these words were presented (Kanwisher 1987; Kanwisher and Potter 1989), and in other in-

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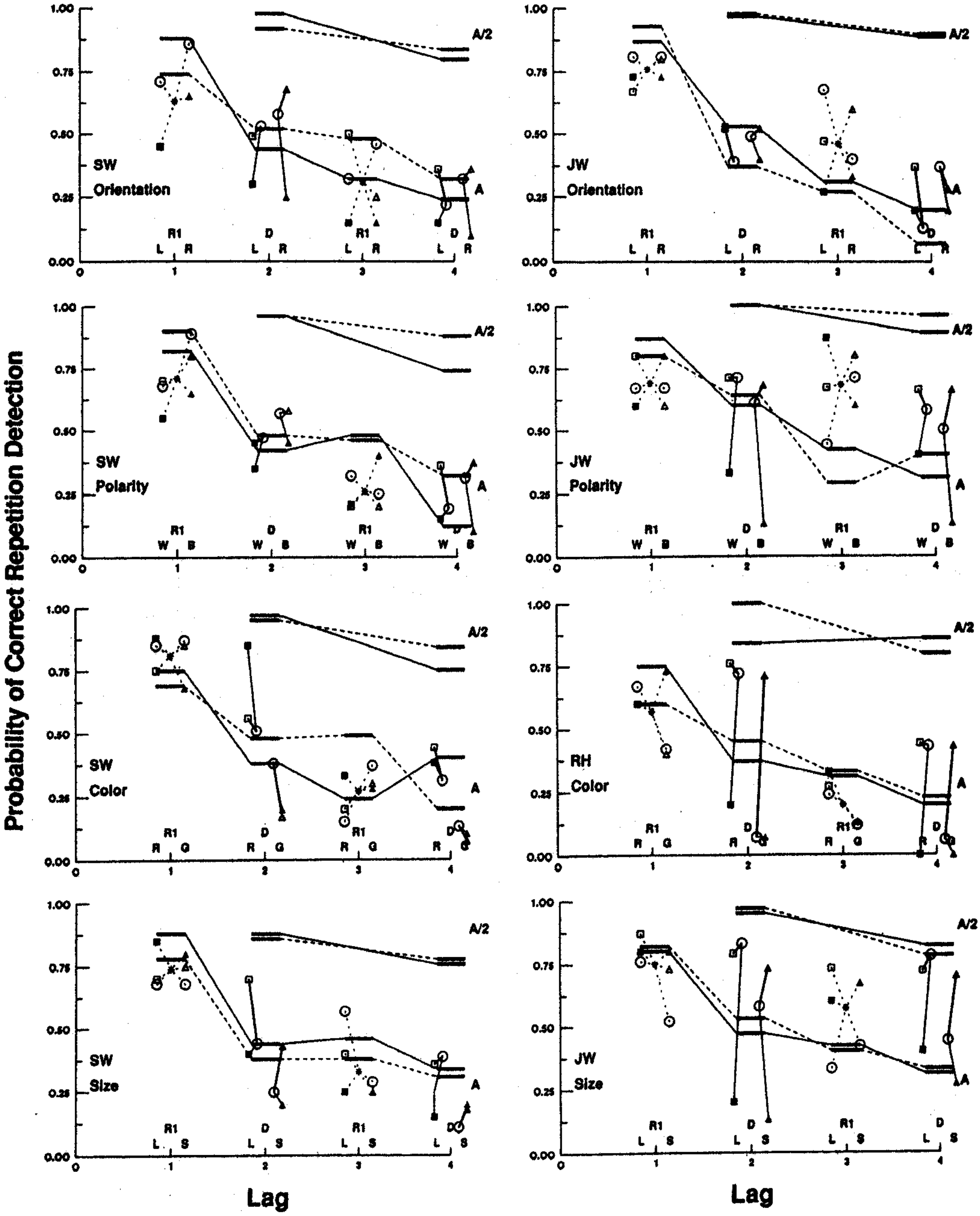
◀ sent attention conditions: squares = Attend-*A*, circles = equal attention, diamonds = Attend-*B*. One standard error is indicated around each point. A and $\frac{1}{2}A$ control conditions are shown on the abscissa, B and $\frac{1}{2}B$ on the ordinate. The clear area defines the reasonable bounds on performance. SW, JW, RH, XL, and ZL indicate subjects; other abbreviations indicate transformations.


Probability of Correct Repetition Detection
SW Orientation
JW Orientation
SW Polarity
JW Polarity
SW Color
RH Color
SW Size
JW Size
A/2
A
R1
D
L R
W B
R G
L S
0.00
0.25
0.50
0.75
1.00
0
1
2
3
4
Lag
Lag

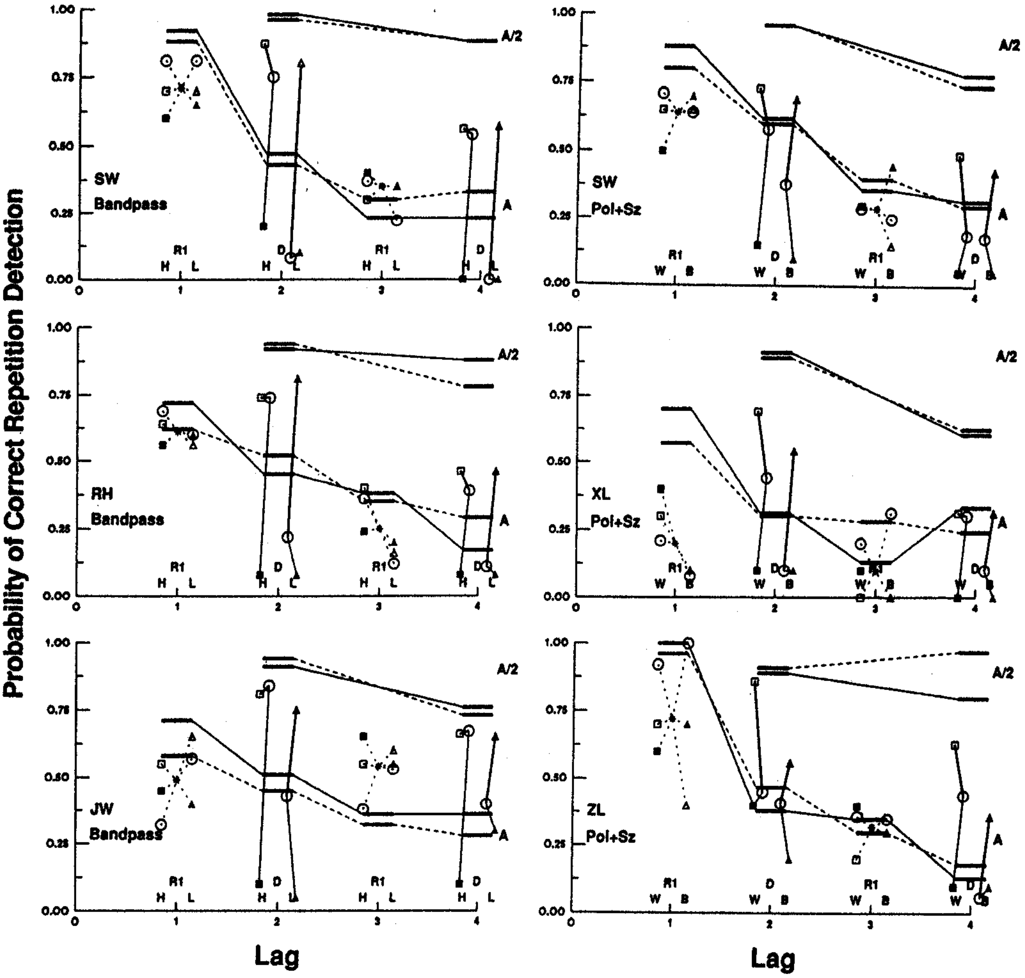


Figure 12.8 Data of all thirty-six trial types for each subject and type of stimulus transformation. In each panel, frame lag is plotted on the abscissa, and proportion of correct detections is plotted on the ordinate. Horizontal bars connected by continuous lines labeled A/2, A, represent control conditions $\frac{1}{2}A$ (control-Blanks) and A (control-All). $\frac{1}{2}B$ and B conditions are indicated by bars connected by dashed lines (not labeled). The data points at each of the frame lags represent the different attention conditions and targets in $\frac{1}{2}A + \frac{1}{2}B$ stimuli. Frame lags 2 and 4 indicate *aa* and *bb* detections; frame lags 1 and 3 indicate heterogeneous *ab* and *ba* detections. Open circles indicate equal attention. At frame lags 2 and 4, data points for the detection of *aa* repetitions are displaced to the left and detections of *bb* to the right, as indicated by dimension labels below (D indicates "detection"). At frame lags 1 and 3, detections of *ab* repetitions are displaced to the left and detections of *ba* repetitions to the right. R1 indicates the first occurring feature in a heterogeneous-repetition pair, indicated by the dimension label below R1. Open symbols indicate detection of the attended feature (even lags) or detection of heterogeneous-repetition pairs in which the attended feature occurred first. Filled symbols indicate reports of unattended features or, in heterogeneous pairs, that the attended feature occurred second. Reports of *aa* (*bb*) under different attention conditions are linked by lines; the heavier line indicates the attended feature. The asterisks at frame lags 1 and 3 indicate the means for the six heterogeneous-repetition types.

stances varying the case of the repetition without incurring a performance detriment (Marohn and Hochaus 1988). These procedural and stimulus differences suggest that repetition-blindness and repetition-detection paradigms may elicit different information-processing strategies and may reflect different levels of processing.

Equivalence of the Opposed Features within a Dimension A glimpse at the control data in figure 12.8 shows that performance on the *A* and *B* control streams is essentially equivalent in all conditions. None of the differences approaches statistical significance.

Feature equivalence means that differential attentional effects exhibited in the $\frac{1}{2}A + \frac{1}{2}B$ conditions are due to factors other than differential discriminability of the streams. Further, we note that attentional effects cannot be due to cross-stream masking in which an item from $\frac{1}{2}A$ masks one from $\frac{1}{2}B$. We refer again to an earlier result that interposing noise fields between successive frames has minimal effects on performance (Kaufman 1978; Wurst, Sperling, and Dosher 1991).

Dominance Relations of Opposed Features within a Dimension Whereas the opposed *A* and *B* features are equivalent when viewed in pure stimulus streams, when they are interleaved in a $\frac{1}{2}A + \frac{1}{2}B$ stream, in the unsymmetric dimensions, one feature may dominate completely. For example, in the color dimension, red is dominant over green. When subject RH attempts to pay equal attention to both colors, she performs exactly as she does when paying selective attention to red (figure 12.7). For subject SW, the color transformation is even more problematical. He is able to selectively attend to red. However, when he attempts to selectively attend to green, his performance on green deteriorates and his performance on red improves. This result was so unexpected that extra sessions were conducted. But the additional trials merely produced more of the same kind of data.

Other examples of dominance are high bandpass over low (subjects SW, RH) and large-white over small-black (subject ZL). The dominance of one feature over another is quite similar to the dominance of one eye over another: Alone, each eye or feature may be equivalent; dominance is observed only when they are placed into competition.

Heterogeneous Detections, *ab* and *ba* In figure 12.8, heterogeneous detections are represented as clusters of points that lie above lags 1 and 3. Because of the strict feature alternation in the $\frac{1}{2}A + \frac{1}{2}B$ stream, different-feature (heterogeneous) repetitions can occur only at lags 1 and 3. The probabilities of these repetitions were quite low, $P = 0.1$ in the selective-attention conditions and $P = 0.14$ in the equal-attention condition (table 12.1). At each of these lags, there are six heterogeneous-detection types: three attentional states × two feature sequences (*ab*, *ba*). All six detection types are illustrated in figure 12.8 for each stimulus transformation, subject, and lag.

Because a heterogeneous repetition involves a feature difference, we expect heterogeneous repetitions to be more poorly detected than same-feature repetitions in all conditions (e.g., Posner et al. 1969, name vs. physical identity matching). The mean of all six heterogeneous-repetition types for lag 1 is below the level of same-feature repetitions in most instances, and dramatically below the same-feature level in some instances (with the exception of subject JW). Further characterization of heterogeneous-detection performance requires a more computational approach; we begin by developing some descriptive statistics of homogeneous detections.

Benefits and Costs in Homogeneous-Repetition Detections

A Computation Example The goal is to characterize selective attention in terms of the efficiency of attentional filtering relative to perfect optical filtering. However, selective attention is studied in the alternating stimulus $\frac{1}{2}A + \frac{1}{2}B$ in which two features are alternated. Feature alternation alone, independent of attention, may have some positive effect on performance relative to All-*A* or All-*B* controls. Therefore, we first consider the stimulus benefit of alternating features.

We begin with an illustrative computation on the data of figures 12.6a and b. Consider the range defined by the two control conditions *A* and $\frac{1}{2}A$. The bottom end of this range represents a point where the *A* and *B* stimuli cannot be discriminated and so performance on $\frac{1}{2}A + \frac{1}{2}B$ is equivalent to performance in either of the controls. The upper end of this range $\frac{1}{2}A$ represents the point where *A* and *B* are discriminated perfectly, and one of them can be ignored perfectly. Therefore, we expect to find attentional effects confined to this range. In figure 12.6a, the range within which benefits might be reasonably be expected to occur extends from .60 to 1.00, a range of 0.40. The equal-attention condition yields a fraction correct of .71, which is $(.71 - .60)/(1.00 - .60) = 0.28$. Attending selectively to *A* also yields a score of 0.71; obviously, there is no additional benefit of selective attention over equal attention. Thus we might conclude that, in detecting *aa* repetitions, there is a stimulus differentiation advantage in the $\frac{1}{2}A + \frac{1}{2}B$ stimuli relative to the All-*A* controls, but no advantage of selective attention.

The detection computations made on *aa* detections in figure 12.6a can be repeated for *bb* detections in figure 12.6b. There is a stimulus differentiation advantage of $(.61 - .64)/(1.00 - .64) = -0.08$, that is, a small cost. The attentional benefit $(.68 - .64)/(1.00 - .64) = +0.10$ also is small.

Finally, we average the *aa* and *bb* results to obtain a stimulus-differentiation benefit of .10 and a selective-attention benefit of 0.05; both of these differ insignificantly from zero by a *t* test. The conclusion is that, for these data, the performance differences between control and experimental stimuli are too small to reach statistical significance. Applying the same computations to the data of figure 12.6d yields an insignificant stimulus-differentiation benefit but a highly significant selective-attention benefit of 0.49.

In summary, the alternating-feature stream, $\frac{1}{2}A + \frac{1}{2}B$, confers two possible benefits: *stimulus discrimination* in equal-attention conditions and *attentional filtering* in selective-attention conditions. To estimate these benefits, it was useful to average the two types of detections (*aa, bb*).

Stimulus-Discrimination Benefit We define the *normalized stimulus-discrimination benefit* as the improvement in equal-attention conditions (equal attention minus control-All) compared to the maximum possible range of improvement (control Banks minus control-All). To compute the stimulus-discrimination benefit (Stim Disc Benefit), the following definitions are needed. Let $P(aa|\frac{1}{2}A + \frac{1}{2}B)_{Attn=A}$ be the probability of correct detections of *aa* repetitions given the $\frac{1}{2}A + \frac{1}{2}B$ stream with attention directed to the A feature. Let A indicate the All-A condition and $\frac{1}{2}A$ indicate the A blanks control condition. Then,

$$\begin{aligned} \textit{Stim Disc Benefit} &= \frac{1}{2}\left[\frac{P(aa|\frac{1}{2}A + \frac{1}{2}B)_{Attn=AB} - P(aa|A)}{P(aa|\frac{1}{2}A) - P(aa|A)}\right] \\ &\quad + \frac{1}{2}\left[\frac{P(bb|\frac{1}{2}A + \frac{1}{2}B)_{Attn=AB} - P(bb|B)}{P(bb|\frac{1}{2}B) - P(bb|B)}\right] \end{aligned} \tag{1}$$

Selective-Attention Benefits and Costs Similarly, the *normalized selective-attention benefit,* abbreviated here simply to Sel Attn Benefit, is

$$\begin{aligned} \textit{Sel Attn Benefit} &= \frac{1}{2}\left[\frac{P(aa|\frac{1}{2}A + \frac{1}{2}B)_{Attn=A} - P(aa|\frac{1}{2}A + \frac{1}{2}B)_{Attn=AB}}{P(aa|\frac{1}{2}A) - P(aa|A)}\right] \\ &\quad + \frac{1}{2}\left[\frac{P(bb|\frac{1}{2}A + \frac{1}{2}B)_{Attn=B} - P(bb|\frac{1}{2}A + \frac{1}{2}B)_{Attn=AB}}{P(bb|\frac{1}{2}B) - P(bb|B)}\right] \end{aligned} \tag{2}$$

where $Attn = AB$ denotes the equal-attention condition.

The selective-attention cost is defined exactly like the benefit in equation 2 except that the subscripts $Attn = A$ and $Attn = B$ are interchanged.

In terms of AOCs, the stimulus-discrimination benefit describes where the equal-attention point lies relative to the two forbidden areas. For example, figure 12.6f shows the AOC derived from subject SW with the polarity stimuli and the same AOC translated up and to the right. The stimulus-differentiation benefit for the real data is 0.14; for the translated data it is .67.

In terms of AOCs, the attention benefit describes how far the arms of the AOC extend outward from the equal-attention point toward the upper and far-right boundaries. For selective-attention conditions, the stimulus and attention benefits sum. Stimulus discrimination measures the extent to which the physical attributes of the items aid in making them discriminable. The selective-attention benefit measures the efficiency of attentional filtering of the unattended items. Together these factors determine how closely attention performance in $\frac{1}{2}A + \frac{1}{2}B$ approaches control performance in $\frac{1}{2}A$ and $\frac{1}{2}B$.

Benefits and Costs in Heterogeneous-Repetition Detections

Heterogeneous-Repetition Cost An alternating stimulus $\frac{1}{2}A + \frac{1}{2}B$ facilitates detections of homogeneous repetitions *aa* and *bb* because the elements of the repetition pair share a common *A* or *B* feature, and this helps to discriminate them from all the other possible pairs, half of which differ in this feature. The benefit of the $\frac{1}{2}A + \frac{1}{2}B$ stimulus becomes a cost when a heterogeneous repetition *ab* or *ba* must be detected.

To estimate the cost of heterogeneous detections, we use a computation similar to the estimation of the homogeneous stimulus-differentiation benefit. In term of the representation in figure 12.8, we measure the distance from the center of gravity of a heterogeneous cluster (the asterisk) to the mean of lower set of curves, divided by the distance between the two sets of curves. There are two complications in locating the appropriate point on the upper curve. At lag 3, we use the average of the upper curve at lags 2 and 4. At lag 1, there is no upper curve, so we simply use 1.0.

$$\text{Hetero Rep Cost} = \frac{\frac{1}{2}(P(ab|\frac{1}{2}A + \frac{1}{2}B) + P(ba|\frac{1}{2}A + \frac{1}{2}B)) - X}{Y - X} \qquad (3)$$

where

$$X = \tfrac{1}{2}(P(aa|A) + P(bb|B))$$

$$Y_{Lag\,3} = \tfrac{1}{4}\{(P(aa|A) + P(bb|B))_{Lag\,2} + (P(aa|A) + P(bb|B))_{Lag\,4}\}$$

and

$$Y_{Lag\,1} = 1$$

For strict comparability with the homogeneous stimulus-discrimination benefit, *P*(*ab*) and *P*(*ba*) should be computed only for equal-attention conditions. However, there was so little systematic difference in heterogeneous detections between conditions that the computation is aggregated over all attention conditions.

Heterogeneous Equal-Attention Benefit In homogeneous-repetition detections, *aa*, *bb*, equal attention was, on the whole, a cost relative to selective attention. Selective attention could filter unattended stimuli prior to STVRM, thereby simplifying the task of repetition detection. Alternatively, attention could operate at the level of memory by tagging the stimuli in STVRM as "attended" or "unattended." Insofar as attention operates prior to storage in memory, attended items are benefited, and unattended items are handicapped. If attention were to operate at the level of memory, either an attended tag or an unattended tag would benefit homogeneous detections relative to heterogeneous detections. As we shall see, there were widespread costs to misdirected attention, and these costs imply an early locus for selective attention.

On the other hand, heterogeneous detections are relatively neutral to an early locus of attention because positively directed attention favors one member of the repetition pair but impairs the other, and the two effects would tend to cancel. But, if attention acted at the level of memory coding, selective attention would impair heterogeneous detections because one member of the pair would be tagged as attended and the other as unattended. Whereas selective attention either at the perceptual or the memorial level would facilitate homogeneous detections, selective attention at the memorial level would be harmful to heterogeneous detections. To quantify this effect, we measure the performance difference between heterogeneous detections with selective attention and with equal attention. This difference is normalized by the same factor as the heterogeneous repetition cost. A positive equal-attention benefit for heterogeneous detections suggests a memorial locus for attention.

Tabulation of Attention Benefits and Costs

Table 12.2 presents the values of five different costs and benefits computed individually for every subject and stimulus transformation. To determine whether an effect was statistically significantly different from zero, a *t*-test was conducted on the numerator of the expression that defines the effect (equations 1–3), and these results also were tabulated. In analyzing the data we concentrate first on the regularities in the data, keeping in mind the very considerable individual differences.

Stimulus-Discrimination Benefits Overall stimulus benefits are quite small. In figure 12.7 this was indicated by the closeness of the AOCs to the lower-left forbidden area. In figure 12.8, it is indicated by tendency of the open circles that represent equal attention to fall on or near the lower curve. Nevertheless there are exceptions: six of twenty-eight stimulus-discrimination benefits are statistically significant; these occur for size, contrast polarity, and bandpass stimuli. There are significant costs for subject SW viewing polarity-and-size.

A stimulus benefit indicates that homogeneous discriminations are facilitated by common features. A cost suggests a significant inability to simultaneously attend to the opposed features, even with equal attention. Apparently, SW can attend either to large-white or to small-black stimuli, but not to both, and therefore performance in an alternating stream suffers relative to the control. (This is further borne out by the large benefits and costs he shows with selective attention for these stimuli.) On the whole, stimulus benefits are small.

Heterogeneous-Repetition Costs Stimulus benefits in homogeneous detections imply stimulus costs in heterogeneous detections. If a common physical feature aids an *aa* detection, the feature difference should impair an *ab* detection. As noted, common features aid homogeneous detections by increasing the distance of the target repetition (which has common features) from the nontarget repetitions that have differing features. This is a relatively small benefit because half of the nontarget repetitions have similar features, and these cause the interference. On the other hand, differing features impair a

Table 12.2 Benefits and Costs Achieved in Equal-Attention and in Selective-Attention Conditions

		Homog Repetition[a]: *aa, bb*						Heterog Rep: *ab, ba*					
		Stimulus		Selective		Selective		Heterog		Equal		Attn	
Stim	Sub	Discr	Benf	Attn	Benf[b]	Attn	Cost[b]	Rep	Cost	Attn	Benf	Type	
		lag = 2	4	2	4	2	4	1	3	1	3	1/2	3/4
OR	SW	.16	−.02	.09	.17*	−.58‡	−.27†	.85‡	−.18*	1.2†	.27*	s	s
	JW	−.06	.13*	.17	.12	.04	−.05	1.4†	.26*	.80	.18	o	o
PO	SW	.14	.05	−.01	.21†	−.24	−.22*	1.1†	−.50‡	.79	.09	o	p
	JW	.10	.32†	.09	.21*	−1.1‡	−.48†	.94†	.53‡	−.19	−.27*	o	r
CO	SW	.03	−.30	−.22*	.02	.29	−.09	.07	−.01	.25	−.03	r	o
	RH	.02	.03	.63‡	.33‡	−.57‡	−.38‡	−.28	−.21	−.09	−.07	p	p
SZ	SW	−.15	−.14	.49‡	.03	−.12	−.18	−.53	−.23*	−.59	.35†	p	s
	JW	.43‡	.58‡	.13	.23*	−1.2‡	−.54†	−.32	.34†	−.84*	−.62‡	r	r
BP	SW	.06	−.06	.67‡	.53‡	−.52‡	−.42‡	1.9‡	.12	1.5*	−.08	b	p
	JW	.39†	.52‡	.29‡	.27†	−1.3‡	−.80‡	.46†	.40‡	−.17	−.24	p	p
	RH	−.05	.00	.70‡	.41‡	−.87‡	−.25‡	−.18	−.24†	.15	−.02	p	p
PS	SW	−.36*	−.28*	.65‡	.61‡	−.91‡	−.30†	1.3‡	−.19*	.31	−.06	p	p
	ZL	.00	.16	.57†	.33*	−.26	−.23	−13‡	−.02	18‡	.11	b	p
	XL	−.06	−.24	.58‡	.30*	−.28*	−.69‡	1.2‡	−.20*	−.22	.42†	p	b

* Statistically significant at: * .05; †.01; ‡.001

a. Benefits and costs averaged over *aa* and *bb* repetitions.

b. Averaged over selective attention conditions.

heterogeneous target repetition relative to the half of nontarget repetitions that have similar features. This is a large cost because it brings the nearest neighbors closer. Nineteen of twenty-eight cells show significant heterogeneous repetition costs; most of these are highly significant. At lag 1, thirteen of fourteen cells show a cost, and nine of fourteen are highly significant. These data indicate that the physical feature is represented in STVRM, and that this feature representation figures prominently in repetition detection. The color dimension is an exception: color similarity seems not to play a significant role in repetition detection.

Feature similarity is a bigger effect for lag 1 than for lag 3. This is consistent with earlier observations (Kaufman 1978) that STVRM for lag 1 seems to be more iconic (less abstract) than for lag 3.

Finally, we note four significant benefits of feature dissimilarity in heterogeneous detections. These all occur for subject JW at lag 3 and characterize all his performances at this lag. Indeed, his performance with heterogeneous repetitions surpasses that of other subjects and at lag 3 surpasses his own for homogeneous repetitions. These data differ profoundly from all our other data and require a different explanation. One possibility that occurred to us is that JW uses the same repetition-detection mechanism that is used in the Kanwisher paradigm (in which longer lags aid repetition detection). If so, making the repeated item different in some physical feature might aid it in surviving repetition blindness. Of the many subjects who have run in our paradigm, JW is the only one who exhibits this effect.

Selective-Attention Benefits All subjects show highly significant attentional benefits for bandpass and polarity-and-size stimuli, and, for each of the other transformations, at least one subject shows a significant attentional benefit. The filtering efficiency of attentional filtering in the bandpass and polarity-and-size stimuli is very high. At lag 2, five of the six cells show a benefit that is 57 to 70 percent of the benefit produced by perfect optical filtering (i.e., the $\frac{1}{2}A$ and $\frac{1}{2}B$ control stimuli).

In multilocation search paradigms, it is not clear whether features merely draw attention to a location or whether information can be filtered according to physical features. In our paradigm, the data indicate that efficient attentional filtering according to physical features occurs within a single location.

Selective-Attention Costs Twenty-six of twenty-eight cells show attention costs for unattended items; nineteen of these costs are statistically significant, and there are no significant exceptions. There is, on the whole, a high correlation between attentional benefits for attended homogeneous repetitions and costs for unattended repetitions. Indeed, if detections of unattended repetitions were not correspondingly impaired, we would have to conclude that attentional selection occurred at a later stage where both attended and unattended items were available for selection.

In spite of the overall correlation between benefits for attended repetitions and costs for unattended ones, there are some obvious exceptions. Subject SW does not have an attentional benefit at lag 2 for orientation or for polarity stimuli but shows a large cost. Subject JW shows a similar effect for polarity stimuli. These observations are consistent with right-angled, concave-down AOCs (figure 12.7) for these conditions that indicate costs without benefits for selective attention.

If unattended items are filtered to the point where detection of unattended repetitions is significantly impaired, should there not be a benefit for the attended repetitions? Finding one but not both of these effects suggests that the unattended items are absent in some contexts (detecting unattended repetitions) but present in others (interfering with detection of attended repetitions). This is one of several indications in our data that attention may operate at more than one level: at a perceptual filtering level before STVRM and at the level of coding information within STVRM itself.

Equal-Attention Benefits in Heterogeneous Detections If the state of attention were coded in STVRM, then we would expect equal-attention conditions to have an advantage in heterogeneous repetitions. On the whole, equal-attention benefits are small; only nine of twenty-eight cells show statistically significant benefits. Of these, three are negative (representing costs). Costs arise in subject JW's data, and the explanation is similar to that considered for JW's heterogeneous-repetition costs. Differentiating repeated items (in this case by the state of attention) facilitates JW's repetition detection.

Patterns of Attentional Benefits

Here we consider joint attentional benefits in detection of homogeneous and heterogeneous repetitions. Figure 12.9 illustrates the four combinations of small or large selective-attention benefits in homogeneous detections with small or large equal-attention benefits in heterogeneous detections. We con-

Heterogeneous *(ab, ba)*
Equal Attn Benefit

Homogeneous *(aa, bb)* **Selective Attn Benefit**	**small**	**large**	
small	**o**	**s**	
large	**p**	**b**	**r**

Figure 12.9 Types of attention performance, according to the joint magnitude of selective-attention benefits in homogeneous-repetition detections and equal-attention benefits in heterogeneous-repetition detections. The letters merely suggest causes: *o* = no attention benefits, *p* = perceptual benefits, *s* = benefits in STVRM (short-term visual repetition memory), *b* = both. The *r* outside the 2 × 2 table indicates reversed effects—impaired performance due to selective attention.

sider an attentional benefit to be large if it is greater than 0.20 and if it is statistically significant. Otherwise it is small. An attentional benefit that is significantly negative indicates impaired performance due to selective attention. Such effects are unexpected and are categorized separately as *r* (reversed). The last two columns of Table 12.2 use a code letter to represent the join distribution of benefits.

No Attention Benefits (*o*) There are five instances of small-homogeneous with small-heterogeneous benefits. These occur in the orientation, polarity, and color stimuli but not in any of the other conditions. The first four of these *o*'s occur in conditions in which there are very large heterogeneous-repetition costs. This demonstrates that these features are highly discriminable; the absence of an attention effect must be attributed to something else. The fifth *o* occurs for subject SW color, which we have already noted is aberrant with respect to attention: attending to green impairs SW's performance for green stimuli but improves performance for red.

Selective-Attention Benefit (*p*); Both (*b*) A selective-attention benefit implies attentional selection of attended items. Perhaps the strongest result in these experiments is the ubiquity of selective-attentional selection in certain stimulus transformations, most notably bandpass and polarity-and-size. For both of these stimuli, all three subjects, at both lags, show a strong selective-attentional benefit (twelve of twelve cells), and in three of these conditions there is also a strong equal-attention benefit (*b*). Even subjects such as JW and SW, who deal quite differently with other classes of stimuli, come together here to show strong attentional effects. Of sixteen remaining cells, only four show a *p* benefit. Clearly, the stimulus dimension strongly influences the ability of subjects to select items according to attentional instructions.

A benefit of selective attention for homogeneous detections without a corresponding penalty in heterogeneous detections (the *p* classification) suggests that attention operates prior to coding in STVRM. The *b* (both) category is ambiguous as to where attentional selection might be operating.

Equal-Attention Benefit for Heterogeneous Repetitions without a Selective-Attention Benefit for Homogeneous Repetitions (*s*) A selective-attention cost for heterogeneous pairs without a selection benefit for homogeneous pairs suggests that attentional selection is occurring in or after STVRM. (If early attentional filtering had occurred, it would have yielded a selective-attention benefit.) The three *s* cells occur when subject SW views orientation or size stimuli. These are additionally coupled with significant heterogeneous repetition cost, indicating that the physical features are represented in memory to the point of interfering with heterogeneous detections. The equal-attention benefit is, alternatively phrased, a selective-attention cost over and above the stimulus heterogeneity cost. For this subject and these stimuli, the evidence quite consistently implies that both features and the attentional state of input items are stored in STVRM.

It is noteworthy that there are significant costs of selective attention connected with two of the three *s* cells and almost significant costs in the third instance. This suggests that selective-attention costs may be occurring at the level of STVRM as well as at an earlier stage.

Reversed Effects of Selective Attention (*r*) These have already received much discussion: subject JW benefits from stimulus heterogeneity, especially at lag 3; and subject SW cannot selectively attend to green (among alternating red and green stimuli).

12.4 SUMMARY AND CONCLUSIONS

Detection of visual repetitions in a rapid stream of items depends on a short-term visual repetition memory (STVRM) that is indifferent to eye of origin and to interposed masking fields, and which functions as well for nonsense shapes as for digits. STVRM is visual, not verbal or semantic. It is governed by interference from new items; it does not suffer passive decay within the short interstimulus intervals under which it has been tested.

Using selective-attention instructions with the repetition-detection task permitted us to test the extent to which, at a single location, subjects could filter rapidly successive items according to their physical characteristics. By presenting all the items at the same location, only attentional selection according to features (and not according to location) is effective. Our subjects selectively attended to subsets of characters based on physical differences of orientation, contrast polarity, color, size, spatial bandpass filtering, and polarity-and-size combined.

Efficiency of attentional selection was determined by comparing performance in a stream of characters that alternated a physical feature with performance in two control conditions: one in which the to-be-unattended characters were optically filtered and another in which all chatacters shared the same physical feature. Selection efficiency in bandpass-filtered streams and in the polarity-and-size streams was greater than 50 percent. Attentional selection based on the other physical features was less effective or ineffective.

Corresponding to the benefits of attentional selection in detecting to-be-attended repetitions, there were large costs in the detection of unattended features. Costs were more ubiquitous than benefits.

In addition to studying repetitions of items that shared a physical feature (homogeneous repetitions), we studied heterogeneous repetitions. Costs for detecting heterogeneous repetitions (relative to homogeneous repetitions) were widespread, indicating that physical features are represented in STVRM. The corresponding stimulus benefits of detecting homogeneous repetitions in feature-alternating streams (under equal attention) were small and only occasionally significant.

If the state of attention were represented in STVRM, we would expect a cost in the detection of heterogeneous repetitions with selective-attention instructions (because the attentional state would differ for the two elements of the pair). Such costs were observed, and in some instances they occurred even when there was no corresponding benefit for selective attention in homogeneous detections. This was interpreted as a lack of early attentional filtering compensated by a memory tag representing whether or not an item was attended.

We conclude that the largest attentional effects occur at the level of attentional selection prior to encoding in STVRM (for bandpass and polarity-and-size stimuli) but that, even when early attentional filtering fails, it can still occur in STVRM.

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REFERENCES

Averbach, E., and Sperling, G. (1961). Short term storage of information in vision. In C. Cherry (Ed.), *Information Theory*, 196–211. Washington, D.C.: Butterworths.

Broadbent, D. E. (1958). *Perception and Communication*. London: Pergamon Press.

Cave, K. R., and Wolfe, J. M. (1990). Modelling the role of parallel processing in visual search. *Cognitive Psychology, 22*, 225–271.

Deutsch, J. A., and Deutsch, D. (1963). Attention: Some theoretical considerations. *Psychological Review, 70*, 80–90.

Duncan, J., and Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review, 96*, 433–458.

Felfoldy, G. L., and Garner, W. R. (1971). The effects on speeded classification of implicit and explicit instructions regarding redundant dimensions. *Perception and Psychophysics, 9*, 289–292.

Folk, C. L., and Egeth, H. (1989). Does the identification of simple features require serial processing? *Journal of Experimental Psychology: Human Perception and Performance, 15*, 97–110.

Garner, W. R. (1978). Selective attention to attributes and to stimuli. *Journal of Experimental Psychology: General, 107*, 287–308.

Hoffman, J. E. (1979). A two-stage model of visual search. *Perception and Psychophysics, 25*, 319–327.

Intraub, H. (1985). Visual dissociation: An illusory conjunction of pictures and forms. *Journal of Experimental Psychology: Human Perception and Performance, 11*, 431–442.

Kanwisher, N. G. (1987). Repetition blindness: Type recognition without token individuation. *Cognition, 27*, 117–143.

Kanwisher, N. G., and Potter, M. C. (1989). Repetition blindness: The effects of stimulus modality and spatial displacement. *Memory and Cognition, 17*, 117–124.

Kaufman, J. (1978). *Visual repetition detection*. Unpublished doctoral dissertation, Department of Psychology, New York University.

Kinchla, R. A. (1980). The measurement of attention. In R. S. Nickerson (ed.), *Attention and Performance VIII*, 213–238. Hillsdale, NJ: Erlbaum.

LaBerge, D., and Brown, V. (1989). Theory of attentional operations in shape identification. *Psychological Review, 96*, 101–124.

Landy, M. S., Cohen, Y., and Sperling, G. (1984a). HIPS: Image processing under Unix. Software and applications. *Behavior Research Methods and Instrumentation, 16*, 199–216.

Landy, M. S., Cohen, Y., and Sperling, G. (1984b). HIPS: A Unix-based image processing system. *Computer Vision, Graphics, and Image Processing, 25*, 331–347.

Marohn, K. M., and Hochhaus, L. (1988). Different case repetition still leads to perceptual blindness. *Bulletin of the Psychonomic Society, 26*, 29–31.

Merikle, P. M. (1980). Selection from visual persistence by perceptual groups and category membership. *Journal of Experimental Psychology: General, 109*, 279–295.

Nakayama, K., and Silverman, G. H. (1986). Serial and parallel processing of visual feature conjunctions. *Nature, 320*, 264–265.

Neisser, U. (1967). *Cognitive psychology*. New York: Appleton-Century-Crofts.

Norman, D. A. (1968). Towards a theory of memory and attention. *Psychological Review, 75*, 522–536.

Parish, D. H., and Sperling, G. (1991). Object spatial frequencies, retinal spatial frequencies, noise, and the efficiency of letter discrimination. *Vision Research, 31*, 1399–1410.

Pavel, M. (1991). Model of preattentive search. *Mathematical Studies in Perception and Cognition, 91–4*, New York University, Department of Psychology.

Posner, M. I., Poies, S. J., Eichelman, W., and Taylor, R. L. (1969). Retention of visual and name codes of single letters. *J. Exptl. Psychol. Monograph, 70*, 1–16.

Reeves, A., and Sperling, G. (1986). Attention gating in short-term visual memory. *Psychological Review, 93*, 180–206.

Runtime Library for Psychology Experiments. (1988). New York: HIP Lab.

Sagi, D. (1988). The combination of spatial frequency and orientation is effortlessly perceived. *Perception and Psychophysics, 43*, 601–603.

Shiffrin, R. M., and Schneider, W. (1977). Controlled and automatic human information processing: II. Perceptual learning, automatic attending, and a general theory. *Psychological Review, 84*, 127–190.

Sperling, G. (1960). The information available in brief visual presentation. *Psychological Monographs, 74* (11, Whole No. 498).

Sperling, G. (1963). A model for visual memory tasks. *Human Factors, 5*, 19–31.

Sperling, G., Budiansky, J., Spivak, J. G., and Johnson, M. C. (1971). Extremely rapid visual search: The maximum rate of scanning letters for the presence of a numeral. *Science, 174*, 307–311.

Sperling, G., and Dosher, B. A. (1986). Strategy and optimization in human information processing. In K. Boff, L. Kaufman, and J. Thomas (eds.), *Handbook of Perception and Performance*. Vol. 1, 2-1–2-65. New York: Wiley.

Sperling, G., and Kaufman, J. (1978). Three kinds of visual short-term memory. Talk presented at Attention and Performance VIII, Educational Testing Service, Princeton, NJ, August 22.

Sperling, G., and Kaufman, J. (1991). Visual repetition detection. *Mathematical Studies in Perception and Cognition, 91–1*, New York University, Department of Psychology.

Sperling, G., and Melchner, M. J. (1978a). Visual search, visual attention, and the attention operating characteristic. In J. Requin (ed.), *Attention and Performance VII*, 675–686. Hillsdale, NJ: Erlbaum.

Sperling, G., and Melchner, M. J. (1978b). The attention operating characteristic: Examples from visual search. *Science, 202*, 315–318.

Sperling, G., and Reeves, A. (1980). Measuring the reaction time of a shift of visual attention. In R. Nickerson (ed.), *Attention and Performance VIII*, 347–360. Hillsdale, NJ: Erlbaum.

Sperling, G., and Weichselgartner, E. (1993). Episodic theory of the dynamics of spatial attention. *Psychological Review*. In press.

Swets, J. (1984). In R. Parasuraman and D. R. Davies (eds.), *Varieties of Attention*, 183–242. New York: Academic Press.

Treisman, A. M. (1977). Focused attention in the perception and retrieval of multidimensional stimuli. *Perception and Psychophysics, 22*, 1–11.

Treisman, A. M. (1982). Perceptual grouping and attention in visual search for features and for objects. *Journal of Experimental Psychology: Human Perception and Performance, 2*, 194–214.

Treisman, A. M. (1986). Properties, parts, and objects. In K. R. Boff, L. Kaufman, and J. P. Thomas (eds.), *Handbook of Perception and Human Performance, Vol. 2*, New York: Wiley.

Treisman, A. M., and Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology, 12*, 97–136.

von Wright, J. M. (1968). Selection in visual immediate memory. *Quarterly Journal of Experimental Psychology, 20*, 62–68.

Weichselgartner, E. (1984). Two processes in visual attention. Unpublished doctoral dissertation. Department of Psychology, New York University.

Weichselgartner, E., and Sperling, G. (1987). Dynamics of automatic and controlled visual attention. *Science, 238*, 778–780.

Wright, C. E., and Main, A. M. (1991). Selective search for conjunctively defined visual targets. Unpublished manuscript.

Wurst, S. A. (1989). Investigations of short-term visual repetition memory. Unpublished doctoral dissertation, Department of Psychology, New York University.

Wurst, S. A., Sperling, G., and Dosher, B. A. (1991). The locus and process of visual repetition detection. *Mathematical Studies in Perception and Cognition, 91–2*, New York University, Department of Psychology.