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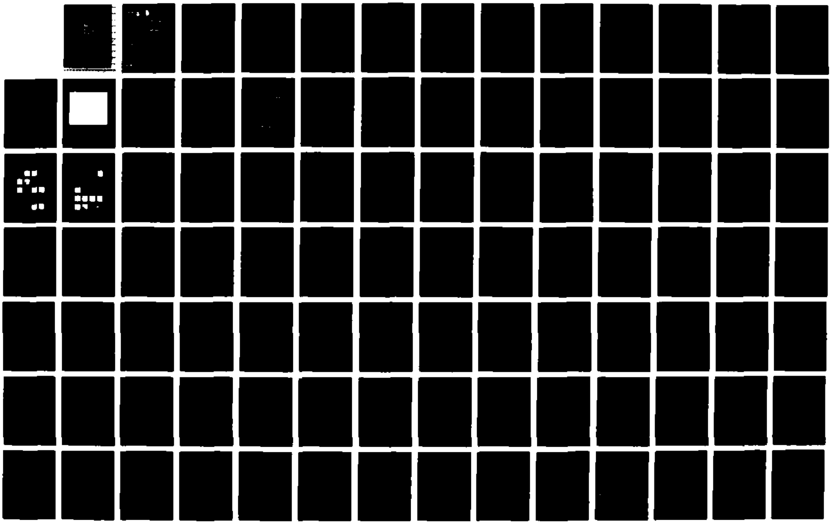

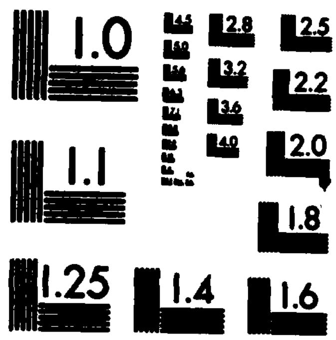

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This report continues our series on the short-term dynamics of human visual memory. We summarize the history of the problem, discuss some properties that define a representation as being visual, outline a new approach embodied in four experimental procedures, consider some general issues of design and analysis in assessing an array-size effect, and report on findings from a set of experiments using the spatial-probe procedure with a visual marker as probe. The principal phenomenon is an effect of array size (3-6 digit elements) on the time to name a visually marked element in a brief visual display that increases rapidly with marker delay, revealing a transformation of the internal representation of the array that is completed within a second. For early markers the effect of array size is negligible, indicating a property of direct access by spatial location. For late markers the effect of array size on mean reaction time is a linear increase. Keywords:

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Direct Access by Spatial Position in Visual Memory: 2. Visual location probes

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Abstract

This report continues our series on the short-term dynamics of human visual memory. We summarize the history of the problem, discuss some properties that define a representation as being visual, outline a new approach embodied in four experimental procedures, consider some general issues of design and analysis in assessing an array-size effect, and report on findings from a set of experiments using the spatial-probe procedure with a visual marker as probe. The principal phenomenon is an effect of array size (3-6 digit elements) on the time to name a visually marked element in a brief visual display that increases rapidly with marker delay, revealing a transformation of the internal representation of the array that is completed within a second. For early markers the effect of array size is negligible, indicating a property of direct access by spatial location. For late markers the effect of array size on mean reaction time is a linear increase.

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Direct Access by Spatial Position in Visual Memory: 2. Visual location probes[1]

1. Introduction: Short-term dynamics of visual memory

Changes in the internal representation of a visual display during the first second after presentation are among the earliest phases of human cognition where memory mechanisms may be investigated. Previous findings indicate that the mental representation of a visual array undergoes drastic change within a second (or less) of its presentation. However, despite more than two decades of intensive research, the traditional account of this critical phase in the assimilation of visual information has come under recent attack. Although most investigators believe that the internal representation of a briefly-presented array undergoes one or more transformations while a person tries to identify and remember the symbols it contains, there is a good deal of uncertainty and controversy about how many different memories or codes must be postulated, when they are available, what their properties are, how long each can be maintained, how the transformation from one to another is accomplished, and how the answers to these questions depend on the particular task and on characteristics of the displayed elements.

The past 25 years have seen considerable research on some of these issues, starting in the early 1960's with Sperling (1960) and Averbach and Coriell (1961). They and others used large, briefly-presented displays--too large for accurate full report--and applied information-sampling methods to estimate the amount of information available at different delays after presentation. The number of letters initially available under these conditions of overload was

1. The series of experiments we report here could not have been done without the expert hardware and software support of A. S. Coriell and W. J. Kropfl. Work other than data collection was supported in part by Contract N00014-85-K-0643 between the Office of Naval Research and the University of Pennsylvania.

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found to be much greater than can be recalled, but after no more than 0.5 sec (depending on visual conditions) it declines to only four or five letters. In the most frequently used information-sampling methods, the item or items to be reported are distinguished by specifying their locations in the display.

Such findings led to the belief in a large-capacity rapidly-decaying visual store, corresponding to the phenomenal experience of a fading image--a store that preserved the display's physical characteristics, and in particular its two-dimensional spatial arrangement. To retain information beyond the duration of this presumed visual representation ("iconic memory") it was believed that a person selected a few characters by naming them covertly, and retained the names in a low-capacity short-term verbal memory, maintained by an active process of covert cyclic serial recall ("rehearsal"). We shall call this final assumed representation a "list memory". Later, Posner & Keele (1967) argued from a reaction-time study of letter comparisons that the internal representation of even a single character changes within a second of its presentation from a visual to a nonvisual form. They also contended, however, that properties of the initial short-lived visual memory in this task differed from those of iconic memory.

In the past few years this traditional view of the short-term dynamics of visual memory has been questioned. Among the important analyses are those by Coltheart (1980, 1984) and Turvey (1978). Two of us began a recent report (Sternberg & Knoll, 1985) by reviewing some of the deficiencies in the traditional view; here we mention just four of several. *First*, the initial representation used as a source of information may not correspond to a phenomenal or visible (and hence visual) representation that is concurrently present. Thus a representation may be present that is visual but is not the source of information when some aspect or position of the display is queried. *Second*, analyses of errors, even in response to probes only briefly delayed, show that identity information can be retained while location information is lost. This seems inconsistent with the fading-image metaphor. *Third*, evidence has accumulated for two distinct non-verbal (and possibly visual) representations, sometimes distinguished as "iconic" and "schematic" (Turvey, 1978), with the latter of limited capacity, long-duration, and not retinotopic, as is the iconic representation (e.g. Scarborough, 1972; Phillips, 1974; Kroll & Parks, 1978; Pollatsek, Raynor, & Collins, 1984; Posner, Boies, Eichelman, & Taylor, 1969). And *fourth*, an alternative interpretation has been advanced for the Posner & Keele (1967) finding, according to which declining activation of a recently-used pattern-identification mechanism, rather than comparison to a fading visual image, is responsible. (Walker, 1978; Proctor, 1981; Kroll & Shepeler, 1985).

These observations reopen the question of the nature of even the initial representation of a brief display that is used as the source of information about it. For example, is it a visual (or spatial) representation? Indeed, what properties ought it to have to be called visual, or spatial, given that it may not correspond to something that is phenomenally visible?

2. Features of a new experimental approach

In this report we discuss the results of a series of experiments using one of four new experimental paradigms we have been employing to investigate changes in the internal representation of visual displays during their first three seconds. (The three other paradigms are briefly discussed in Sections 4 and 21 below; detailed treatments can be found in Sternberg, Knoll, & Leuin, 1975; Sternberg & Knoll, 1985, and Turock, 1985.)

As mentioned above, previous research has been primarily concerned with arrays of characters large enough to produce overload, and has explored the resulting rapid information loss from visual memory by assessing the frequency and pattern of errors. In contrast, our aim is to work with arrays that are small enough so as not to overload the memory system or systems that underlie display processing: we wish to understand performance under conditions where it is virtually errorless, even after a long delay.

Four of the arguments that justify this objective are as follows. First, conditions associated with high accuracy characterize many real-world situations; furthermore, they may call upon mechanisms different from those used in the overload conditions that have traditionally been investigated. Second, it seems likely to us that subjects choose among a larger set of alternative "strategies" for coping with the task when their error rates are higher, thereby creating greater challenges to good experimental control. Third, the study of conditions of overload (with its emphasis on error analysis) is incompatible with investigation of the virtually perfect performance that is possible when a display is actually present, of interest from the practical viewpoint and important theoretically (see Section 3.1, e.g.). Finally, despite the great importance of the early studies, and considerable subsequent research effort, the goal of understanding performance under conditions of overload has not been realized: For example, Coltheart (1984, p. 282) has concluded that "we still do not understand in any detail how to explain the basic results of the partial report experiments of Sperling (1960) and Averbach and Coriell (1961)."

By applying time pressure to the subject under conditions that produce high accuracy, the experimenter can induce some of the mechanisms at work to reveal themselves, not by how they fail, but by how much time they need to succeed. Our desire to analyze the processing of information in terms of its functional components, particularly when combined with the hypothesis that some or all of the component processes are arranged in stages (Sternberg,

1969) leads naturally to reaction-time (RT) methods and to an interest in the temporal structure of processing. The power of RT methods as compared to others lies partly in the fact that the appropriate scale of measurement can be specified on the basis of relatively weak assumptions. This means that quantitative aspects of data such as additivity and linearity of effects come to have powerful implications. Because of the linear effect of array size in the data to be discussed, these considerations are important in the present report.

In a typical experiment an array of from one to six letters, digits, or other visual forms is briefly presented.[3] Either before, during, or at various delays up to about 3 sec after the display a probe is presented, querying the subject about information in the array. The subject is instructed to complete his or her response as rapidly as possible after the probe, consistent with accuracy. We use the RT pattern to index the retrieval process, and use aspects of and changes in this pattern to make inferences about the internal representation on which the retrieval is based. Given our desire to sample a rapidly-changing representation at a time controlled by the probe delay, eliciting a response under time pressure appears to have a special advantage over *ad lib* responding: There is more reason to suppose that information is retrieved from the representation in the state in which the probe finds it, rather than after further transformation.

It is well to bring out the inferential heuristics that are implicit in the arguments we use and central in the interpretation of our findings. First, if two probe delays produce different RT patterns, then either (a) the internal representations that provide the information differ, or (b) the retrieval processes differ, or both. If a change in probe delay altered the retrieval processes with *no* change in internal representation, this would require explanation. In the absence of arguments to the contrary, we therefore conclude that any difference between RT patterns at different probe delays is caused by a change in the internal representation. Second, suppose that the RT pattern can be shown to be sensitive to *some* changes in conditions. Then if

3. We have used horizontal linear arrays almost exclusively. A frequently used alternative, in which the position of an element in the array is not confounded with retinal eccentricity, is an arrangement where elements fall on an imaginary circle at whose center is the fixation point. For several reasons we prefer linear arrays: designs involving the circular arrangement often confound mean separation between adjacent elements with array size; visual anisotropies imply that position on the retina can be ignored in neither case; we believe that linear arrays place any "strategies" of ordered "scanning" under better experimental control; in some procedures the response depends on a specification of direction, and left versus right seems to require less practice than clockwise versus counterclockwise; and finally, where we have compared performances with linear versus circular arrays (Sternberg, Knoll, & Leuin, 1975), gross aspects of our findings are similar.

two conditions, such as two probe delays, produce (approximately) the same RT pattern we conclude, in the absence of arguments to the contrary, that the internal representations that provide the information, as well as the retrieval processes, are (approximately) the same. Since we expect any transformation of the internal representation to be progressive, it follows that the RT pattern that is observed at one probe delay should not recur at a later delay if it changes at all between those two delays.

A critical feature of our approach is the use of a range of array sizes; indeed we have found the effect of array size on mean retrieval time to be the data of most central interest. One reason is that this effect has proved to be remarkably orderly: At a given delay, the function relating mean RT to array size (the *RT function*) is often approximately linear, and, moreover, parameters of this linear function change in an orderly fashion with probe delay. A second reason is that our earliest work revealed that whether mean RT increases or decreases with delay of the probe depends on array size: restricting an investigation to a single array size could be quite misleading.

In each of our paradigms, therefore, we have been concentrating on the interaction between probe delay and array size (how probe delay alters the effect of array size on RT) rather than investigating the main effect of probe delay (how probe delay alters RT.) If the RT can be regarded as a sum of the durations of a series of processing stages, then all stages contribute to the RT, whereas presumably only a subset of stages (only those whose durations are influenced by array size) contribute to the array-size effect. Because they depend on fewer processing stages, then, interactions between array size and experimental factors of interest are likely to be associated with fewer separate mechanisms than the main effects of these factors, and thus to be more useful for inference. That is, investigation of the interaction between array size and probe delay offers the promise of isolating a subset of all the processes influenced by probe delay.[4]

4. For discussions of possible meanings of interactions involving RT measurements, see, for example, McClelland (1979), Sternberg (1969, 1984), and Townsend & Ashby (1983).

3. Some possibly diagnostic properties of representations that are visual

Once we admit the possibility that the initial representation from which information is retrieved may not correspond to the phenomenal representation, and hence may not be visible, we are led to consider properties other than visibility that might be diagnostic of a visual representation. Ultimately a set of such properties might come to be regarded as necessary -- *defining* a visual representation.[5] We have considered and attempted to test for the first five of the following six such properties:

3.1 Memory-display equivalence

Performance based on a visual memory should be similar to performance observed when a visual display is actually present, except possibly for effects that can be attributed to degradation. Thus, for example, temporal properties of retrieval, such as the effects of array size on the time to respond to a probe (sometimes interpreted as scanning rates), should be approximately equal for memory and display. Testing for this property requires the use of prolonged displays (displays that permit accurate performance) -- not consistent with the traditional approach, in which the analysis of error frequency is central.

3.2 Directional symmetry

A visual representation of a row of characters should be capable of being scanned either left-to-right or right-to-left, just as an actual display can be scanned either way by eye movements. That is, scanning in the two directions should be possible, and should be accomplished by the same kind of process. We do not require that the process proceed at the same rate in the two directions. (This property generalizes in obvious ways to two- and even three-dimensional layouts.)

3.3 Direct access by spatial position

An element should be accessible directly by spatial location. Thus, there should be no effect of the *number* or the *arrangement* of other filled locations on the time to extract information from a properly-specified target location.

5. It should be kept in mind that in the course of processing a visual display, two or more distinct representations may be generated - successively, simultaneously, or as alternatives - all of which might possess a sufficient number of suitable properties to be called visual. For example, a representation, R_1, which showed effects of retinal position might be replaced by R_2, which did not, but both R_1 and R_2 might show the effects of geometric transformation of the displayed elements.

3.4 Selective processing at a location

It should be possible for an element at a target location to be processed selectively, such that there is no effect of the *content* of other locations on the time to extract information and respond. Thus, array items in other locations that would produce response competition if recognized (Eriksen & Schultz, 1979) should have no effect.

3.5 Sensory linkage

Characteristics of performance known to result from features of the visual system should apply to a visual representation. An example is the effect on identification time of the retinal position of an array or element.

3.6 Modality-specific interference

Performance based on a visual representation should be especially subject to interference from a secondary task that involves a visual display. Initially, Brooks' (1968) findings seemed to exemplify the discovery of such a property; later findings suggested that the interference effect should be reinterpreted as interference by a spatial (rather than specifically visual) secondary task with performance based on a spatial (rather than specifically visual) representation (e.g., Baddeley & Lieberman, 1980).

4. Summary of findings from the identity-probe and probed-reciting procedures

In this section we outline two procedures we have applied in pursuing the approach described in Section 2, and in testing for properties listed in Section 3. In these procedures (as well as the new procedure discussed below) we present a variable-size array of no more than six digits, and a probe to elicit a response that depends on information in the array.

In the *identity-probe procedure*, the probe is the spoken name of one of the items in the array (presented under computer control); the correct response is the spoken name of the item in the array to the right of the probe. At all delays between array and probe--both negative and positive--we found the RT function to be linear, suggesting a simple search process (Sternberg, Knoll, & Leuin, 1975). Parameters of the linear function change sharply between delays of zero and about 0.65 sec, however: the slope approximately doubles (from about 55 msec/item to 100 msec/item), suggesting halving of the search rate, while the intercept drops by about 200 msec. When probe delay reaches 0.65 sec, effects of the display's position on the retina that are evident at shorter delays have vanished, suggesting that an initially "raw" visual representation is no longer visual (or is at least abstracted to some degree); at this delay the retrieval process appears much like retrieval from the memory of a serially-presented list. Finally, performance with an early probe is unaffected by prolonging the brief display, evidence for the first of the properties listed in Section 3. A visual identity probe produces similar results.

We devised the *probed-reciting procedure* as a way of testing for the directional-symmetry property. Here, the probe is a tone burst; the subject must recite all the items in the array either forward (left-to-right) or backward (right-to-left), depending on the tone's frequency. In one variant of this procedure, the tone and required direction are fixed for a block of trials *(directional certainty)*. In the other variant, the required reciting direction varies randomly from trial to trial *(directional uncertainty)*. Under directional certainty, the reciting RT for a zero-delay probe grows surprisingly rapidly (about 100 msec/item) with array size (Sternberg & Knoll, 1985). As the probe is delayed, RT is reduced and the slope of the RT function *declines*, in contrast to the effect described above in the identity-probe paradigm.[6] An asymptote appears again to be reached within 1 sec. Thus, under directional certainty, we find that at brief delays, when the search rate in the identity-probe procedure is fast, the display has not yet been converted into a form that permits rapid reciting, whereas at longer delays, when search is slower, it has. Uncertainty about reciting direction has little effect at short delays. But at a probe delay of one sec, performance is markedly impaired by such uncertainty. This finding suggests that information in the initial "visual" memory is stored in a form that has no particular directionality (i.e., the directional-symmetry property of Section 3.2 applies), but that directionality is an inherent aspect of the nonvisual memory code that follows.

Similarity of the time courses of the effects in the probed-reciting and identity-probe procedures suggests the same underlying transformation. Other aspects of the data conflict with this interpretation, however. For example, details of the reciting data suggest that during the RT for a zero-delay probe the displayed items are processed sequentially and in an order that depends on the required reciting order. If the transformation were sequential in the identity-probe procedure, however, rather than parallel, we would expect the RT functions to be nonlinear at intermediate probe delays, contrary to our observations. In Section 18 we describe a quantitative test of a similar hypothesis of sequential transformation applied to our results with visual

6. In this procedure the function relating mean RT to array size is markedly nonlinear at some delays, so the slope must be regarded as no more than a convenient measure of the average effect per array element on mean RT.

location probes. Every one of several models we have examined that is a specific realization of this hypothesis does indeed produce concave downward functions at intermediate delays. A second issue raised by findings in the reciting paradigm depends on the observation that even after a delay of 3 sec, reciting in an unexpected direction is far more rapid (and more accurate) if the initial presentation was an array than if it was a serially-presented list. One possibility is that even after a long delay in the former case, two distinct representations are simultaneously available to the subject, one nonvisual and with inherent directionality, and the other visual and directionally symmetric, but perhaps degraded (Parks & Kroll, 1975).

5. The spatial-probe procedure

We were led to the spatial probe procedure by our desire to test for the property of direct access by spatial position (see Section 3.3). Given an appropriate specification of position within the array, and assuming that the direct access property obtains, it follows that information about the element in the specified position should become available with approximately the same delay, regardless of the number or arrangement of other elements in the array. We say "approximately" because there may exist (for example) lateral interference effects mediated by peripheral visual mechanisms that influence legibility, and hence response latency, or possibly that influence visual latency directly. Insofar as such an effect occurs, its magnitude would tend to be confounded with number of other array elements and also would depend on the arrangement of these elements. A second proviso is implicit in the term "appropriate specification of position": To gain access to the information at a particular "address" in a memory, one must know how to specify that address. If the functional address has to be "computed" from the address provided, then the duration of this computation may depend on the number of occupied addresses. In consequence, an inappropriate mode of addressing a memory may lead one to observe effects of the number of occupied addresses, even while an appropriate addressing mode would not.

The addressing mode we have used is a visual marker, consisting of two vertical line segments, one above and one below the location of one of the elements of the array. Markers similar to this have been used as single-element partial-report cues in studies of memory for large arrays in which accuracy rather than latency was assessed (e.g. Averbach & Coriell, 1961; Mewhort, Marchetti, Gurnsey, & Campbell, 1984).[7] One of our displays is shown in

Figure 1, and a schematic is shown in Figure 2.[8] The display has three constituents, which can appear and disappear at different times: One is the array of numerals itself. Six array locations are defined, subtending a visual angle of 3.5°. The smaller arrays are not necessarily centered in the display area, since we wish to reduce the confounding of array size with distance from the fixation point. Instead, the smaller arrays occupy a subset of contiguous locations, chosen randomly from the possible subsets. (For an array of size s there are $7-s$ possibilities.) The distributions of array sizes and locations were the same as those used in our work with linear arrays in the identity-probe procedure, as were the exposure conditions; we wished to make quantitative comparisons between results from the spatial- and identity-probe procedures. Arrays were presented for 150 msec.

The second display constituent shown in Figure 1 is a pair of dots associated with each array position that contains a digit, one above and one below the digit. These "registration dots" appeared simultaneously with the array itself, but whereas the array was presented for 150 msec, the dots remained on until the response was detected. We believe that the presence of the dot pairs averts difficulties associated with loss of registration of marker with array that might develop with long delayed markers.[9]

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7. It is important to distinguish these applications of spatial probes from those where the information conveyed by the probe is redundant with other information in the display (e.g. Eriksen & Yeh, 1985; Holmgren, 1974; Kahneman, Treisman, & Burkell, 1983; Yantis & Jonides, 1984). Thus, in one type of experiment an array of characters contains one of two (or more) targets in a location that varies unpredictably, and may also contain one or more nontargets; the subject must determine which of the two (or more) targets is present. In a second type of experiment the display contains either one of a specified set of targets plus one or more nontargets, or nontargets only; the subject must respond as to whether a target is present. In both types of experiment a visual marker can then provide information about target location that is redundant, in the sense of not being required for the correct choice of response. Because of the marker's redundancy, which permits the subject to "choose" whether to use the information it conveys, we regard these procedures as more complex than those in which the marker must be used if a correct response is to be made on an acceptably high proportion of the trials. Such redundancy also characterizes the spatial probe procedure if the array contains only one element; it is partly for this reason that our smallest arrays are of size two.

8. Displays, produced by a cathode-ray oscilloscope with a fast (Hewlett-Packard P4) phosphor, were calibrated photometrically. Each displayed dot had a time average luminous intensity of approximately 19.0×10^{-6} cd; it was intensified about once per msec. Thus an entire matrix of intensified dots with the same intensification rate and spacing as the dots in the displayed digit would produce a photometer reading of about 8.0 ftL (see Sperling, 1971). The background screen luminance was about 0.01 ftL. These conditions matched those used by Sternberg, Knoll, & Leuin, 1975, in the identity-probe procedure. (See Section 4 of the present report.)

9. Lowe's results (1975) indicate that even with brief delays such registration marks improve the discriminability of marker location.

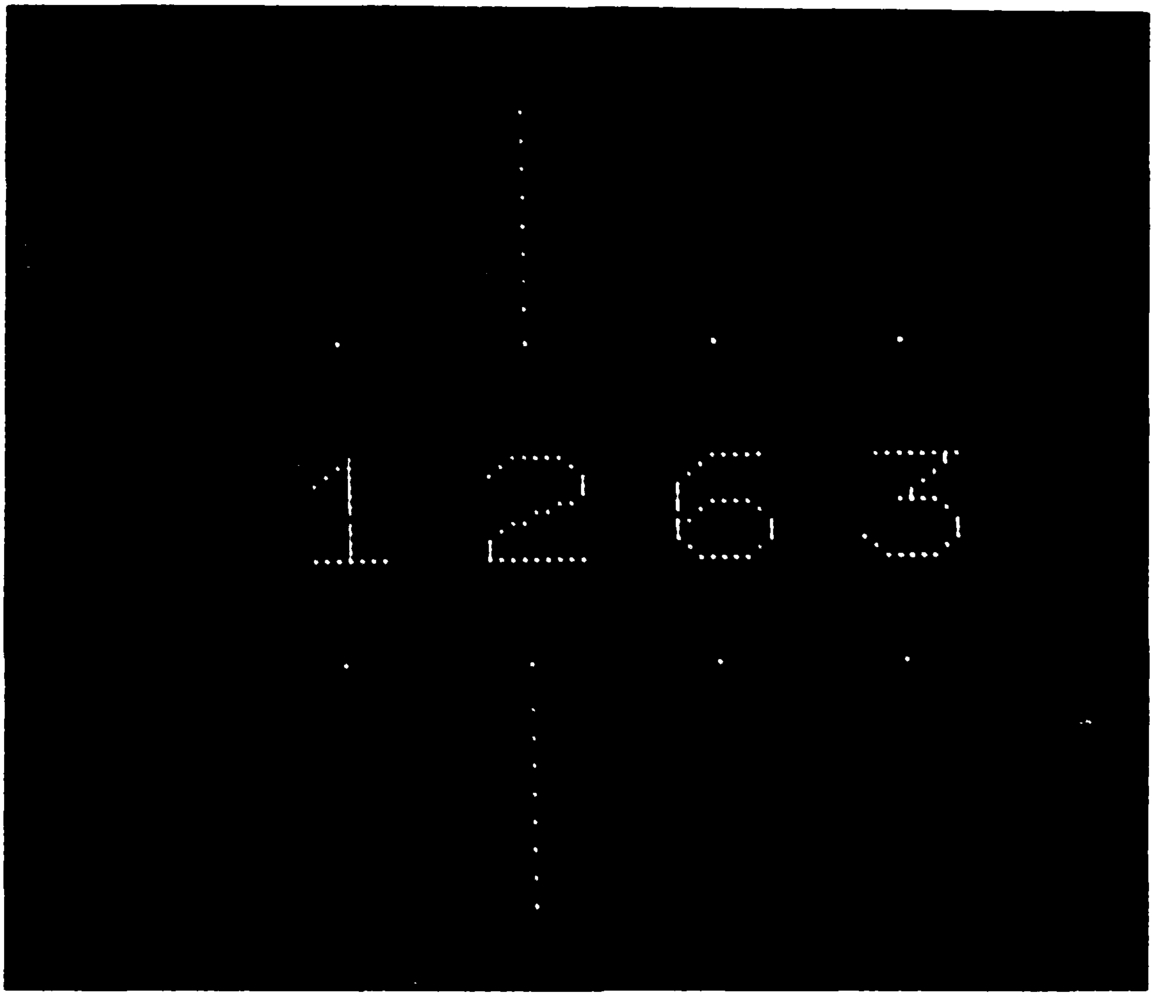

Figure 1.

The third display constituent is the location marker, two line segments defined by a vertical rows of dots that extend outward from each of the registration dots associated with the target digit. The marker was presented for 50 msec. The probe delay is defined as the time interval from onset of array to onset of marker, and can take on positive (lagging probe) or negative (leading probe) values.

A noise-burst warning (duration 0.5 sec) followed by a visual fixation pattern (duration 1.3 sec) were presented before the onset of the first of the three display constituents described above.

Three of the possible time sequences of array, registration dots, and marker are described in Figure 3. In all three examples the correct response is to pronounce the word "eight." In the first example probe delay is zero. The 50 msec probe and the 150 msec array turn on simultaneously. In the second example the probe immediately follows the array, so the probe delay is 150 msec. The final example shows a long delay. Here the dots are especially useful in reducing subjects' difficulties of registration of array and marker. The dots stayed on until the response.

The subject's task was to name the "target digit" (the one in the probed location) as fast as possible, consistent with accuracy. We measured vocal RTs from either the onset of the array or the onset of the marker, whichever came second. Registration dots remained on the screen until the speech detector and computer registered the spoken response. Subjects were paid for speed and penalized for errors.

6. Design issues in assessing an array-size effect

In this section we discuss some of the issues that must be considered in designing experiments that use the spatial-probe procedure. (In a modified form these issues are also relevant to numerous other experimental paradigms where effects of array size are of interest.) Readers not interested in this level of detail may omit this section and still comprehend later sections.

As discussed in Section 2, our principal interest is in the effect of array size on mean RT-at different probe delays: Array size and probe delay are our primary experimental factors. Other (secondary) factors that might have effects on RT, or are known to have such effects, may also vary from trial to trial. (Examples are the target element's *identity*, its *serial position* within the array, and its *absolute position* within the display area.) Such variation is sometimes required to avoid enabling the subject to make predictions that would affect performance differentially over levels of one or both primary factors. Ideally, we should arrange that all secondary factors are independent of array size and probe delay, either by being held constant while the primary factors are varied, or by being varied orthogonally with the primary factors.

That is, the same set of levels of each secondary factor should appear with each (level of) array size at each probe delay. Furthermore, for each pair of secondary factors that interact, it is also necessary (ideally) to arrange that all members of the cartesian product of their sets of levels appear with each level of array size at each probe delay. (Because exact balancing may often be achieved statistically -- by an appropriately-weighted average -- equalizing of trial frequencies at different levels of a factor is often not essential; adjustment of trial frequencies may be more important in relation to subjects' expectancies than for avoiding spurious effects due to confounded variation.)

With respect to probe delay it is easy to achieve this desired independence for most of the secondary factors: Our approach has been to specify a set of arrays and marker positions, and use this same set at each delay. (Note, however, that if the delay is great enough -- either negative or positive -- to permit an eye movement to occur between presentation of array and marker, and one does, this will probably disturb the independence of some secondary factors with respect to probe delay.) With respect to array size there are inherent difficulties, however, such that any design reflects a set of compromises. Here we list some of the factors that are of concern to us in this connection, and indicate the design compromises that we have made. We refer to the element in the marked location as the "marked element".

6.1 Serial position

The marked element has a serial position (1, 2, ..., s) within the array and may, in particular, be either an *inside element* -- with a neighbor on each side (positions 2,..., $s-1$), or an *end element* -- with one neighbor only (positions 1,..., s). An array of size one (a size we did not use in the present series of experiments) contains a third type of element: an *isolated element* -- with no neighbors. Because isolated elements are distinctive, in that they appear only in arrays of one size, there is no way to separate the effects of isolation on the one hand, and of array size one *versus* greater than one on the other. Serial position is of possible importance for at least two reasons. One is that in a search process, position of an element in the array may be systematically related to its position in the search order, which in turn may influence RT. The other is that whether an element has neighbors on one or both sides may influence its legibility and also the extent of response competition.

As it is not clear how to identify which are corresponding serial positions in arrays of different size, and as the number of levels of the serial position factor depends on array size, levels of this factor cannot be balanced across array size. Because some models (in particular, some search models) provide predictions for the mean RT over serial position -- predictions that do not depend on the pattern of RTs across positions -- we have averaged across positions within array size with equal weights. Note that if there is an effect of

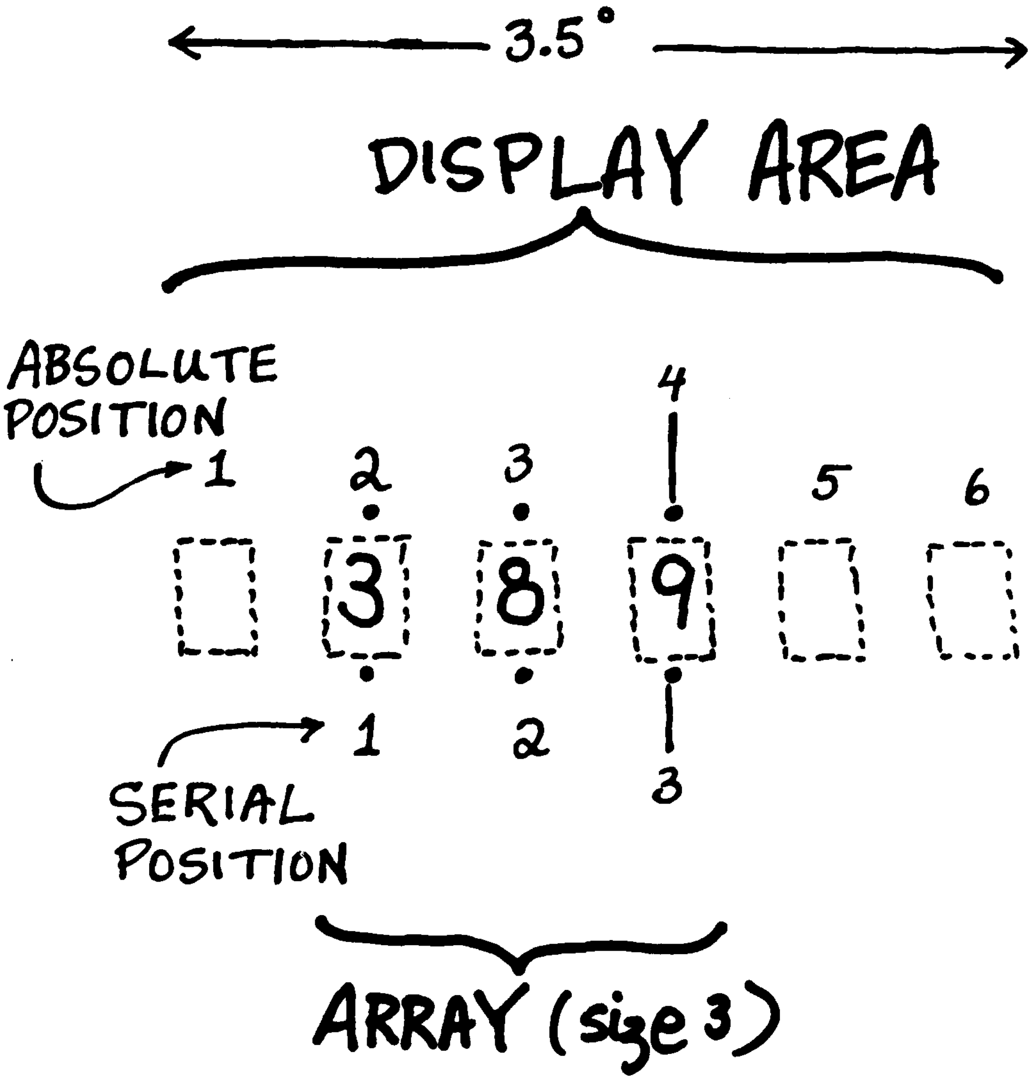
3.5°
DISPLAY AREA
ABSOLUTE POSITION
1
2
3
4
5
6
3
8
9
1
2
3
SERIAL POSITION
ARRAY (size 3)

Figure 2.

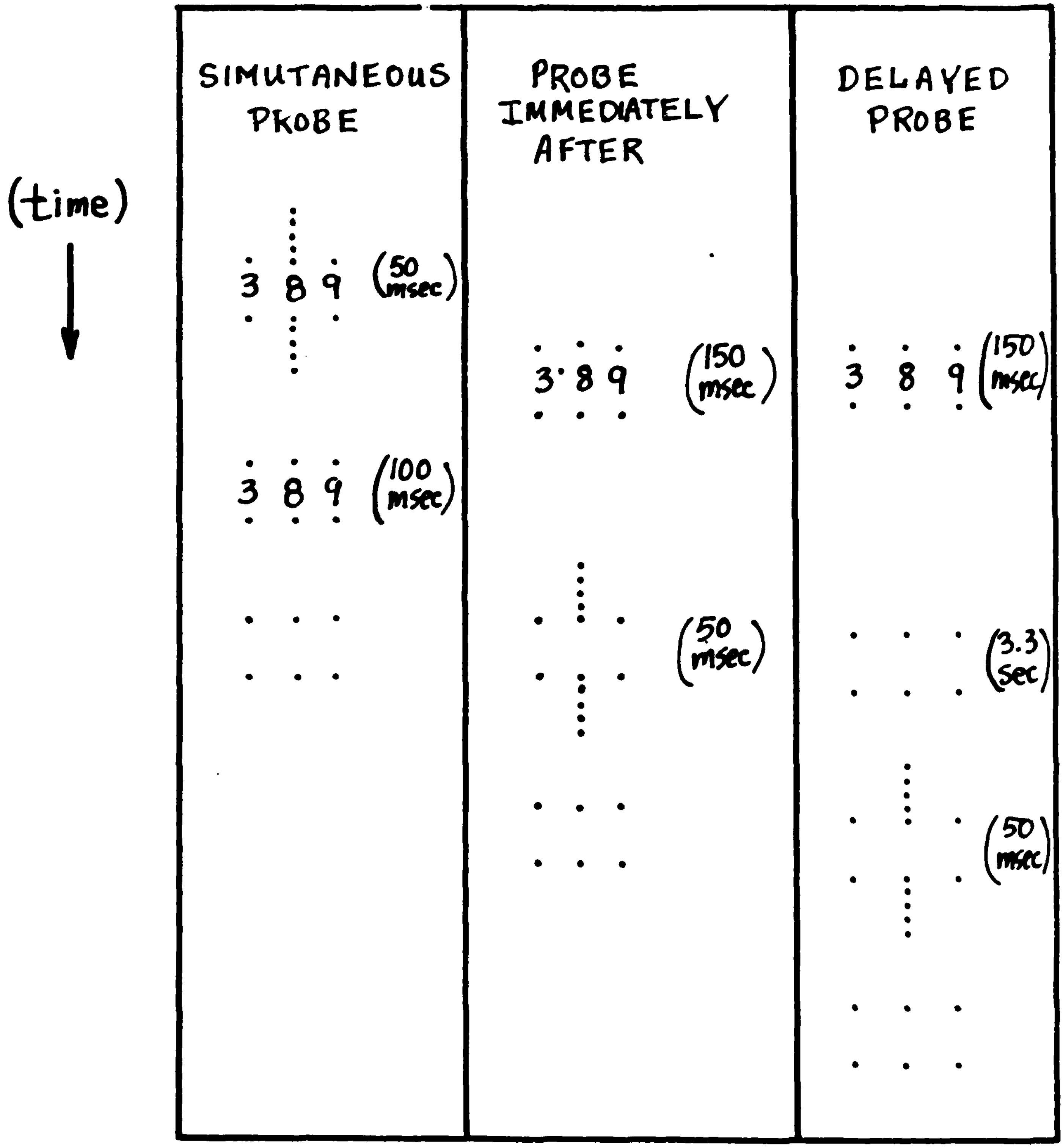
(time)
SIMUTANEOUS PROBE
PROBE IMMEDIATELY AFTER
DELAYED PROBE
3 8 9
(50 msec)
(100 msec)
(150 msec)
(50 msec)
(150 msec)
(3.3 sec)
(50 msec)

Figure 3.

an element's occupying an inside versus end position that is independent of array size, then this *end effect* could contribute spuriously to an array-size effect, because end elements contribute relatively more to an equally-weighted mean for small arrays than for large arrays.

6.2 Separation between adjacent display elements; Spatial extent of the array

We have elected to hold the separation between adjacent display elements constant as array size is varied, to maintain both the required level of discrimination of marker location, and any lateral interference effects of adjacent elements; hence our choice (mentioned above) of having each array occupy a contiguous subset within the six display locations. As a consequence of this choice, the spatial extent of the array is confounded with number of array elements (array size).

6.3 Absolute position of the marked element

There are six possible positions within the display area; we would like each of them to be used (equally often) for each array size. This factor is important for at least two reasons. One is that the times required for both marker discrimination and element identification may depend on retinal eccentricity. The other is that the subject's spatial uncertainty about the marker and the marked element may have an effect by virtue, for example, of how she allocates visual attention over the display area (see, e.g., Shaw, 1978; Shaw, 1984; or LaBerge, 1984). We therefore arranged trial frequencies so as to approximately balance absolute position over array size.

6.4 Position of array within display area

As mentioned above, there are $7-s$ possible positions for an array of size s. (Given serial position, r, and absolute position, a, of the marked element, array position is $a-r$, which can take on the values 1, 2,..., $7-s$.)

An alternative design choice would have been to use centered arrays, so that there would be one position for an array of a given size, rather than several. Had we done this, the separation of absolute-position effects from array-size effects would have required us to make unpalatable assumptions about the effects of serial position.

6.5 Retinal locus of marker

We believe that subjects follow the instructions to fixate the center of the display area before the array or marker appears. (Regrettably, however, we have not checked this belief rigorously by actually measuring eye position in these experiments.) For positive or negative probe delays that are within about 200 msec of zero (too short a time to permit a saccade), the absolute position of the marked element therefore determines the marker's locus on the retina. For lagging markers, however, long probe delays permit the eyes to move. Our data suggest that the fixation then shifts to the approximate center of the set of array locations (which at all positive probe delays are indicated by the registration dots). Marker eccentricity (and hence probably the time required to discriminate the marker) then becomes confounded with array size: mean distance from fovea to marker increases with array size. In the analyses presented in the present report we have not tried to deal with this problem.

6.6 Retinal locus of marked element

For markers that lead the array by more than about 200 msec it is possible that fixation shifts from the center of the display area to the location of the marker. If this occurs then at such delays the marked element is always fixated, probably reducing the time required for discrimination of both its position and its shape. Since this fixation shift would presumably occur for all array sizes it would not lead to a serious confounding with array size at any particular probe delay. But since it would occur for some probe delays and not others, the effects of such a shift would be confounded with probe delay. In the experiments described in the present report the leading markers lead by no more than 50 msec, so that this confounding of probe delay and retinal locus of target element does not arise.

6.7 Response element

For several reasons we expect measured naming latency to vary systematically from one digit to another, whether the name is derived from a visual or transformed representation. (Possible reasons include differences in visual discriminability, differences in the time required to arrive at the spoken name from the derived identity, and differences in latency of the speech detector across speech sounds.) We therefore attempted to balance response element over array size.

7. Design of Experiments 1 - 5

Because of our desire to match the conditions of the new spatial-probe experiments with the earlier identity-probe experiments (Section 4), we used the same arrays in the two sets of experiments, and arranged that the response digit associated with each array was the same. Consider an array of size s in the identity-probe experiments, and let $k = 1, 2, \ldots, s$ represent serial position from left to right. If the probe is the spoken name of the element in position k then the correct response is the spoken name of the element in position $k + 1$. Because of this relationship, probe positions in the earlier experiments ranged over all except the rightmost element: $k = 1, 2, \ldots, s-1$, while positions of correct responses ranged over all except the leftmost element: $k = 2, \ldots, s$. Marker locations in the new experiments therefore ranged over all array positions except the leftmost.[10]

We conducted five experiments to examine the effects of marker delay on the RT function. Each experiment was conducted with the same set of four subjects, and the five experiments included observations of different but overlapping sets of probe delays. In all experiments, we fixed probe delay for blocks of about 150 trials, while varying array size randomly from trial to trial with approximately equal frequencies at each of four values: $d = 3, 4, 5$, and 6.

In a simple design we would probe the s serial positions for each array size (or $s-1$ positions, when we match the identity-probe procedure) with equal frequency. Because of the distribution of array positions, however, this would lead to unequal frequencies over absolute positions, as follows. The arrays occupy contiguous display locations among the set of six possible locations, giving $7-s$ possible locations of the whole array for an array of size s. In a simple design, trial frequencies would be equal over this set of possibilities. Given uniform frequency over serial position (within array position) as well, trial frequencies could not be equal over absolute positions. Instead, for all except array size $s=6$, frequencies would be lower for more extreme absolute positions. Especially for short probe delays (too short to permit the subject to appreciate which are the occupied absolute positions and to reallocate attention) this nonuniformity may induce subjects to restrict their attention, and neglect the extreme absolute positions. We therefore compensated by supplementing trials in the simple design with added trials with arrays whose first (or last) element was in the first (or last) absolute position, and for which we probed that first (or last) position. Trial frequencies were thus no longer equated over array position and serial position. However, we restored the desired balancing over levels of these factors *statistically* by averaging over them with equal weights rather than the more usual weights (which would be proportional to trial frequency). As we analyze the RT's only of clearly-spoken correct responses, trial frequencies equated in the design are only approximately equal in the data; such statistical balancing handles this problem also.[11] The ten digits occurred as responses with approximately equal

10. In later spatial-probe experiments to be reported elsewhere (and summarized briefly in Sternberg, Knoll, & Turock, 1985) we relaxed this restriction, and distributed the probes over all occupied locations. This permitted us also to extend the range of array sizes downward to $s=2$. Results are qualitatively the same.

11. We are in the process of reanalyzing these data using a multiple linear regression model in which absolute position is one of the variates, to generate a less clumsy solution for this problem and others. Initial comparisons suggest no qualitative changes in outcome, but indicate that the more primitive analysis we used may generate small biases in estimates of some

frequency for each array size.

Within each experiment the set of probe delays was presented in an order that was balanced *over* subjects. In each of Experiments 3, 4, 5 there were four delays. In each replication the order of conditions for each subject was given by one row of a 4x4 bigram Latin square. (In a *bigram square*, each condition follows each other condition equally often.) In successive replications, the order of conditions was reversed, so that in each pair of successive replications, any linear component in the practice effect would be balanced over probe delays *within* subjects.

As in Experiments 3, 4, and 5, Experiment 1 had four conditions, and we used the same methods to balance the order of running them. Two of the conditions involved the same long probe delay, however. Because this delay was long (3.45 sec), it was likely to induce more time uncertainty (about when the probe would appear) than the other delays. We felt it was important to determine whether such uncertainty plays a significant role in controlling performance. Thus, in one of the two 3.45 sec conditions we also included a warning signal, a 2400 Hz signal of 60 msec duration presented 1.3 sec before the marker appeared. (This interval approximately matches the foreperiod for a zero-delay probe.) Because the results with and without the warning signal were virtually the same, we have averaged the data from these two conditions in the present report.

In Experiment 2 there were only two conditions, run in an order that was balanced over subjects, and reversed in successive replications.

To reduce the likelihood that subjects would shift their eyes from the center of the display area to the position of the marker (and hence of the target digit) before array offset, we used negative probe delays that were no greater than 50 msec, so that the time from marker onset to array offset was never greater than 200 msec; this value is usually exceeded by saccade latency. In units of seconds, then, probe delay ranged from -0.05 to 3.45, over the set of five experiments.

We used the same four female subjects in this series of experiments as in the preceding series with the identity probe (Sternberg, Knoll, & Leuin, 1975); as a consequence they had worked for 28 days with brief displays in a closely related task before beginning. For each subject the present series of experiments involved 26 days of testing, or about 8000 trials.

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parameters. For example, the slope of the RT function may be overestimated by about 5 msec.

8. Design of Experiment 6: Auditory sequence

Findings with traditional methods, as well as our previous research with small arrays, led us to expect systematic change in the pattern of retrieval times as the probe was delayed--a change that reflects transformation of the internal representation of the array. At which probe delay can we assert that such transformation is complete? If there is just one transformation, or a series in close succession, then one answer is the delay beyond which the retrieval-time pattern shows no further change. If one or more transformations are completed, and then followed after a further delay by one or more others, we would expect the retrieval-time pattern to be invariant during that further delay, even though it might change thereafter: In such a case the corresponding criterion would then be the delay at which such a period of invariance begins. We hoped that Experiments 1-5 might reveal such a point.

An alternative criterion for completeness of the transformation is the probe delay at which the retrieval-time pattern becomes invariant with respect to input modality--if such a delay exists. (Other, analogous criteria would depend on invariance with respect to other stimulus attributes, such as retinal locus, blur, or distortion.) We would then infer that such invariance also applied to the representation on which the retrieval process operates. We conducted Experiment 6 to permit us to search for such a point of modality-invariance.

After a warning signal a set of registration dots appeared on the screen, the number of dot pairs and their locations varying in the same manner as in the trial sequences in Experiments 1 - 5. The corresponding numerals never appeared on the screen, however. Instead, they were presented through headphones as spoken digits, at a rate of two digits/sec, under computer control. The duration of each word was approximately 250 msec. Subjects had been instructed to associate each digit in sequence, as it was presented, with the corresponding left-to-right position of the registration dots concurrently displayed. The first word in the sequence began 0.75 sec after onset of the dots. We allowed 2.50 sec after the end of the final word in the sequence before the 50-msec marker appeared. The task was to name the digit in that ordinal position in the auditory sequence that corresponded to the probed location on the screen. The dots remained on the screen until the speech detector and computer registered the subject's response.

The RT data we report for the auditory sequence condition are derived from the first two of three sessions with the procedure, run after Experiments 1 - 5. The comparison with array conditions might thus be confounded with a practice effect. To insure that this was not the case, we also ran an array condition with a probe delay of 1.65 sec, paired with a third auditory session in an order that was balanced over the four subjects. Mean slopes in this final pair of sessions were almost identical for the two conditions.[12]

9. Results: Accuracy

The mean error rate over the set of experiments was about 3%, a good level for experiments whose main purpose is the measurement of RT, but the errors were not distributed uniformly over conditions. Error rates derived from Experiments 3, 4, and 5 are shown for each probe delay as a function of array size in Figure 4. For purposes of this analysis, data were pooled over absolute and serial position for each array size. As will be seen, error rate and mean RT behave similarly. For the shortest probe delay, there is no effect of array size. As probe delay increases to 350 msec and beyond, the pattern changes radically, and error rate comes to rise precipitously with array size. Indeed, at long delays, with arrays of size $s=6$, the rate is sufficiently high (about 12%) so as to make the RT data somewhat suspect; fortunately the RT data for correct responses are sufficiently orderly so as to allay our concerns.

10. Results: Mean reaction-time functions

For a specified probe delay and array size, s, each trial has at least three additional attributes known to influence RT: (a) which of the ten possible digits is associated with the probed location, (b) which of the s possible serial positions in the array (which we designate starting with the leftmost position) is occupied by the probed digit, and (c) the absolute position probed in the space of six possible positions within the display space (which we designate starting at the left). The effects of each of these factors on RT, and especially changes in their effects with probe delay, are of considerable interest, but their discussion will be deferred to another report. For the present treatment we combined data over levels of these factors by ignoring (i.e. pooling over) digit identity and array position and averaging with equal weights over serial position.

Mean RT for correct responses in each of the six experiments is shown as a function of array size at each delay in Figures 5A and 5B. Each plot shows one RT function together with a line fitted by least squares; plots are arranged in columns associated with probe delays, and in rows associated with experiments. A time line indicating probe delay is shown at the top of each figure; delays start at −.05 sec (or −50 msec) at the left, and become positive

12. As these data are not reported below, we mention here that the slopes were 75.4 and 77.6 msec/element for the sequence- and array-condition, respectively, in the last two sessions. The mean slope for Experiment 6 (the first two auditory sequence sessions) was similar: 69.9 msec/element.

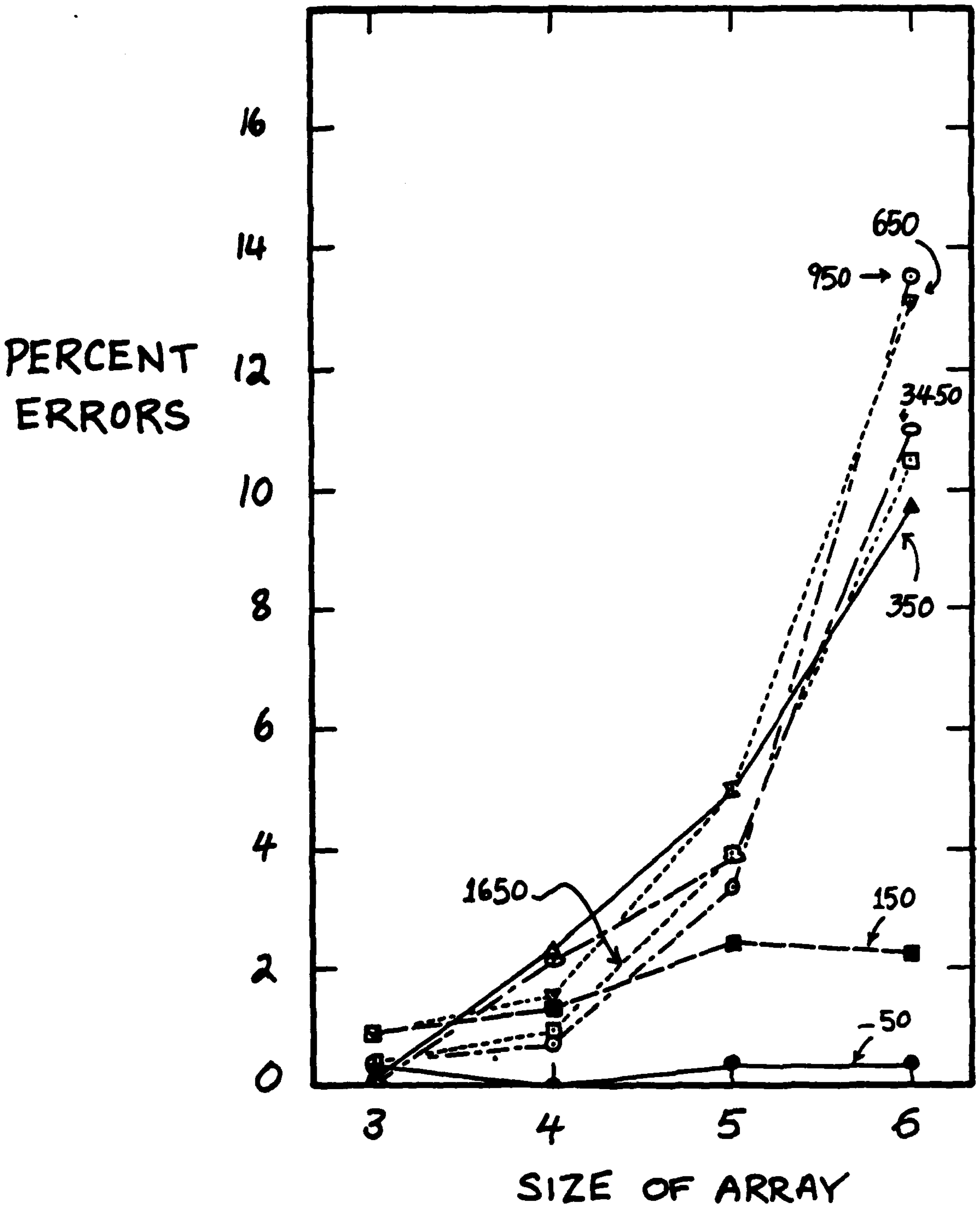

PERCENT ERRORS
16
14
12
10
8
6
4
2
0
3
4
5
6
SIZE OF ARRAY
650
950
3450
350
1650
150
50

Figure 4.

and increasing to the right.

Several features of the results are evident without further data reduction. In general, the fitted linear functions described the data well, except for a few of the functions at longer delays, where slight upward concavity is suggested. The linearity will justify our characterizing the data in terms of parameters of the fitted lines. For almost all delays we examined performance in more than one experiment; functions for a given delay tend to show small but systematic reduction in height with increasing practice, whereas the slopes of functions from different experiments show good agreement.

The RT function is strongly and systematically influenced by probe delay. Consider first the data in Figure 5A. For the earliest probes, i.e., for markers that begin (delay 0) or end (delay −50 msec) with the onset of the array, the effect of array size on mean RT is negligible, just as is its effect on error rate (shown in Figure 4 for −50 msec probes). This is evidence for the direct-access property. Even after a short delay, however, an effect of array size emerges: the direct-access property appears to be rapidly lost. Note, however, that without an estimate of the time required to discriminate the marker, we cannot state at what point in its life the internal representation of the array is addressed by a probe at any particular delay, including the earliest. That is, we do not know the effective probe delay. Hence without further argument or evidence we cannot assert for which period during the life of the internal representation the direct access property applies. (On the basis of a simple view of the required events, it seems likely that the effective probe delay is greater than the physical delay: The time to represent the marker display at the relevant place(s) in the visual system plus the time to discriminate the marker's location and apply that information to the array is greater than the time to represent the array at the relevant place(s) in the visual system. If so, a probe with a physical delay of −50 msec, for example, could easily have an effective delay that is greater than zero.)

The plots for longer delays (Figure 5B) show that by about 2/3 sec the change in the RT function is essentially complete: the effect of array size has reached an approximate asymptote, with the slope about 80 msec/element; there is little further systematic change, even with delays as long as 3.5 sec.

The plots in Figures 5A and 5B show that the direction of the effect of probe delay on mean RT depends on array size: performance becomes faster for the small arrays, but slower for the larger ones.

These conclusions are supported by two analyses of variance of the RT means, based on data combined for common delays across experiments. Before combining the data we first adjusted for effects of practice on mean RT from one experiment to the next, which we assumed to be independent of delay and array size. (The adjustment is described in more detail in Section 13.1.) For each pair of values of delay and array size we then determined the arithmetic

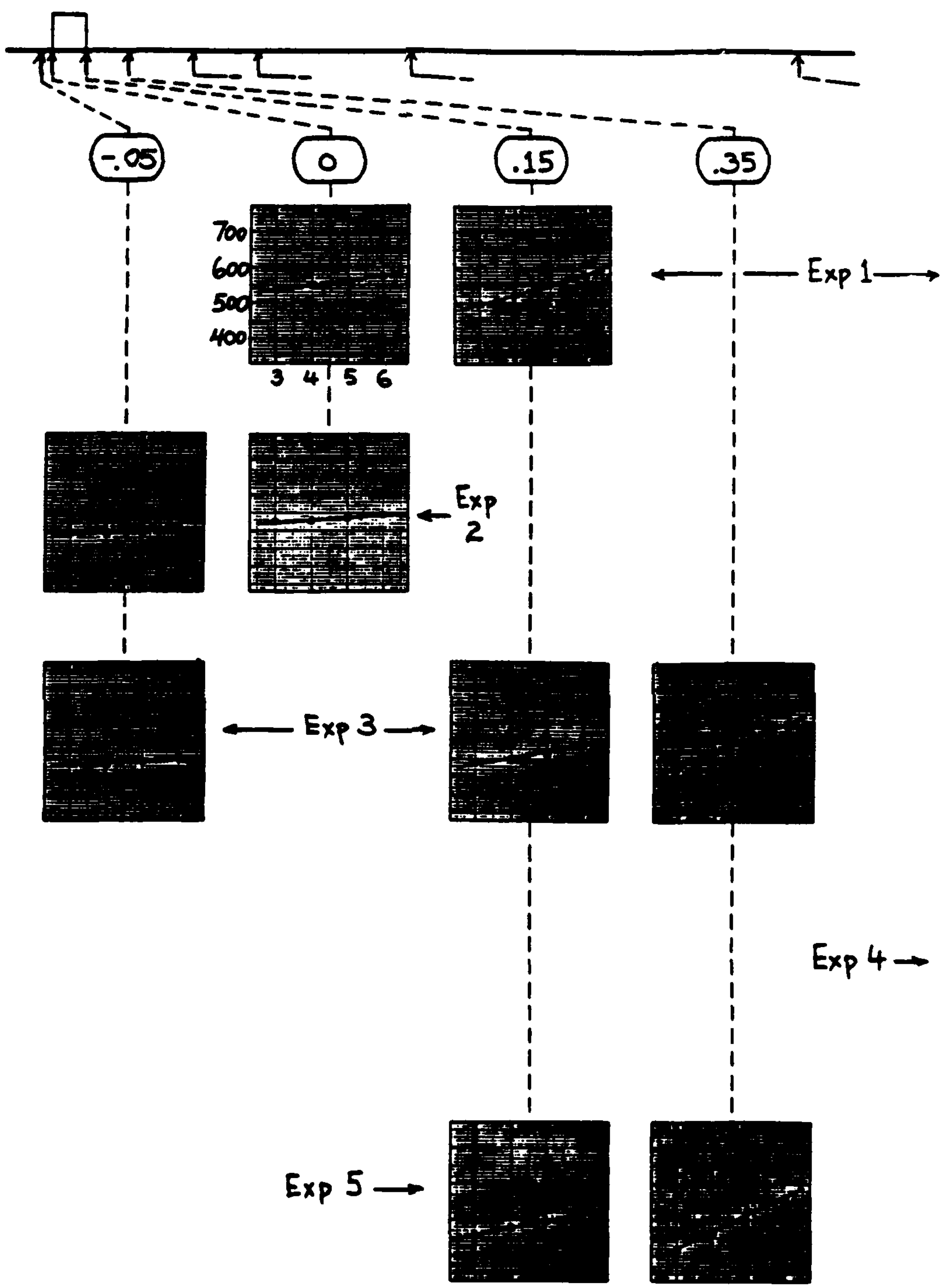


Figure 5A.

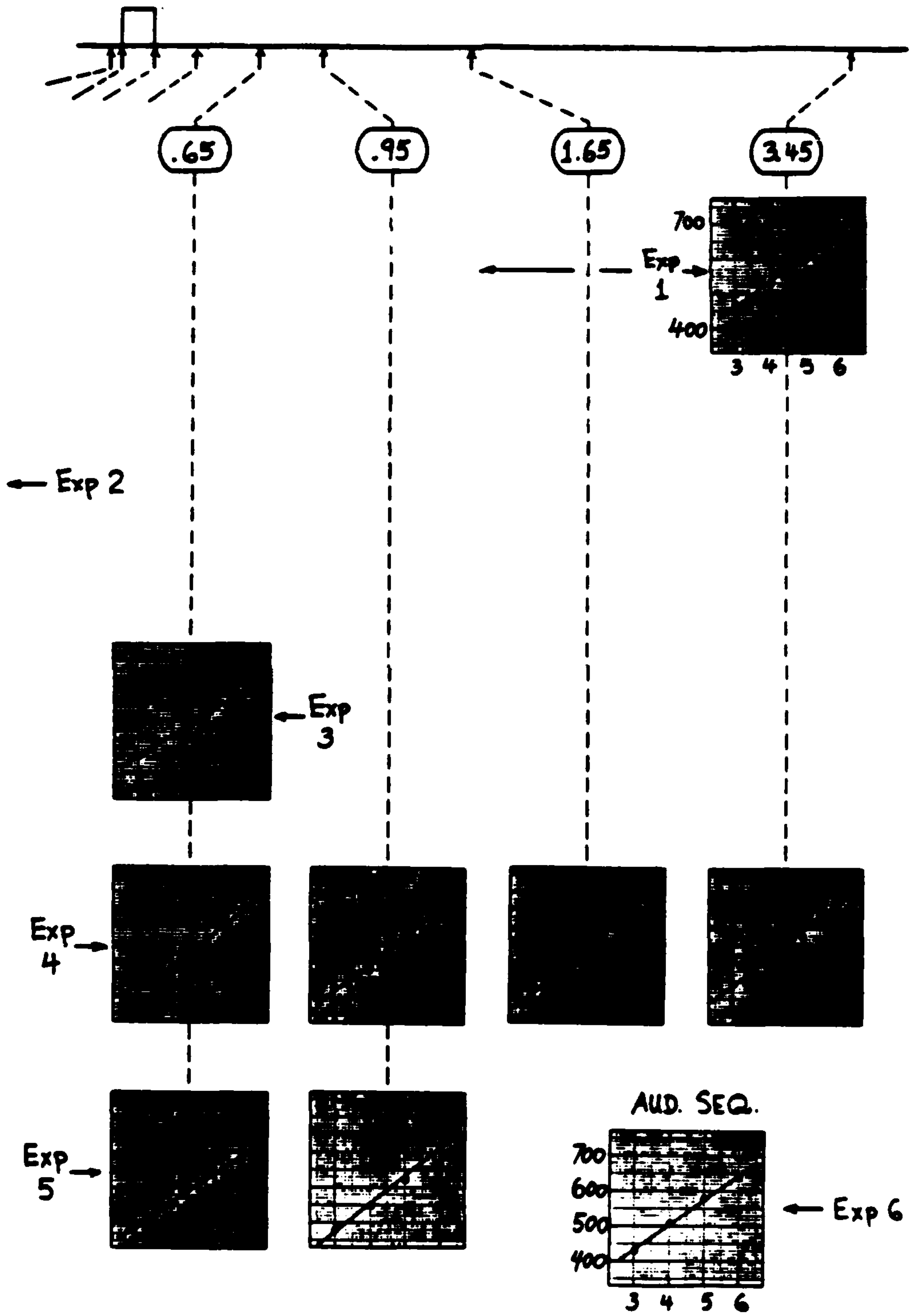

.65
.95
1.65
3.45
700
400
3 4 5 6
Exp 1
Exp 2
Exp 3
Exp 4
Exp 5
AUD. SEQ.
700
600
500
400
3 4 5 6
Exp 6

Figure 5B.

mean over all the experiments in which it was studied. This process provided us with a complete factorial arrangement of four array sizes and eight delays, for each of our four subjects. The first analysis of variance was of the full data. Here the interaction of delay and array size was highly significant [$F(21,63) = 12.4$], where the error term is the triple interaction of delay, array-size, and subjects. (Given the significant interaction, the main effects of the interacting factors are not especially interesting.) We performed the second analysis to determine whether performance continued to change beyond a probe delay of 950 msec. The analysis was limited to the subset of the data that included only the three longest delays (950, 1650, and 3450 msec). Here array size produced the only reliable effect [$F(3,9) = 22.3$]; neither the effect of delay nor its interaction with array size was significant.

In the lower right corner of Figure 5B is shown the RT function for Experiment 6, in which the information usually conveyed by the visual array was presented as an auditory sequence. The data are similar to those for a visual array after less than a second, further evidence of the completeness of the transformation. The data thus meet both of the criteria for completeness of the transformation discussed in Section 8, and at approximately the same probe delay.

11. Results: Reaction-time variance functions

There are at least three reasons why the reaction-time variance in these experiments may be of considerable interest, in addition to its obvious usefulness for experimental design and inferential statistics about means. First, for any delay, the relation between the increase in variance and the increase in mean as array size grows can be used to test models of self-terminating search. (See Appendix 7 in Sternberg, Knoll, & Leuin, 1975, for an example of such a test applied to data from the identity-probe paradigm.) Second, for any array size, the relation between the change in variance and the change in mean, as probe delay grows, can be used to test the possibility that rather than reflecting a gradual change in the internal representation, the smooth change in performance reflects a change in the probability that the internal representation is in one or the other of two discrete (and very different) states (i.e., a binary mixture mechanism). See Section 17 and Appendix 1 below for such a test. Finally, if the property of direct access by spatial position (Section 3) obtains at any delay, then just as there should be no effect of the number or arrangement of other filled array locations on the mean of the distribution of the time to extract information from a properly-specified target location, so there should be no effect on its variance. Because of the possible importance of the variance, we use the present section to provide results of initial analyses.

11.1 Statistical balancing over serial position

One of our objectives is to examine our data in relation to a hypothetical process of self-terminating search. In such a process the search time depends on the target's position within the search order, or the *search-order* position. As experimenters we can control the target's *serial* position in the array. However, because the subject (rather than the experimenter) controls the starting point and possibly the order of search, we cannot separate trials on the basis of search-order position, which depends on these variables as well as on serial position. Fortunately it is possible to derive predictions from such search models if targets occupy the possible search-order positions with equal probability. Given plausible assumptions, this equal-probability condition can be guaranteed if trials are pooled in such a way that serial positions are represented equally frequently within the pool. In the actual data, however, they are represented unequally (Section 7), which requires us to achieve the balancing statistically. For the mean this involves simply averaging with equal weights over serial position. For the variance the problem is slightly more complicated. The problem can be phrased as that of estimating the pooled variance of a population containing equal-size subpopulations (with means and variances that might differ), from data in which sample sizes of the subpopulations are unequal.

Let $i = 1, 2, \ldots, m$ index the set of possible serial positions, let s_i^2 be the (unbiased) sample variance for serial position i, let $T_{i,j}$ be the jth sample value for that serial position, let n_i be the sample size for that serial position, let $T_{i\cdot}$ be the corresponding sample mean, and let $Var(T_{i\cdot})$ be the (unbiased) sample variance of the set of such means. Then it can be shown that $Var(T_{i,j})$ can be estimated without bias by

$$Var(T_{i,j}) = \frac{1}{m}\sum_i \left(\frac{n_i - 1}{n_i}\right) s_i^2 + Var(T_{i\cdot}). \tag{11.1}$$

11.2 Two different variances

For different purposes, two different variances seem appropriate, and so we attempted to estimate both.

Overall variance In estimating the "overall variance" we applied the expression above to the raw data. As an alternative estimator of dispersion in this case we also used a robust estimator: the *MAD* (median absolute deviation from the median). To adjust for the unequal representation of serial positions discussed above we used Equation 11.1, replacing each sample variance by the square of the corresponding *MAD*, and replacing the variance of the sample means by the square of their *MAD*. Note that some tests are defined specifically in terms of the variance, so the *MAD* or MAD^2 may be an inappropriate substitute.

Residuals variance To estimate the "residuals variance" we applied Equation 11.1 to the residuals after fitting our linear regression model to the data. (See Footnote 10 in Section 7.) We used robust regression for this purpose, because it appears to provide better estimates of the true means than least-squares regression. Note, however, that our estimator of the residuals variance (about the relevant mean) was the ordinary sample variance rather than a robust estimator of dispersion.

Rationale for two different variances Why estimate two different variances? For some tests all effects that contribute to the variance should be included in the variability measure, rather than be removed by regression. For other tests, only the effects of those factors that contribute to to the variance by influencing the position of the target in the order of a purported search *(search-order position)* should be included. For still other tests, even such effects should be removed. One difficulty is that we are not certain which factors influence search-order position. Serial position seems likely to be one, and target identity seems unlikely to be, while our intuitions are less clear about absolute position. We therefore chose two variances that are at the extremes, one that removes the effects of all three of these factors (residuals variance), and another that removes the effects of none of them (overall variance).

11.3 Combining of Variance Estimates over Subjects

Ranges of the reaction-time variances (and their values) differ considerably across subjects. Combining without first normalizing the data for individual subjects would therefore produce a structure in which subjects were unequally represented. Instead, where we used the variance as the dispersion statistic we applied the following procedure: The 75%-point was determined for the set of (48) variances for each subject.[13] To normalize, we then divided each variance in the set by the 75% point. We obtained the median of the four variances (one per subject) derived from corresponding conditions and array sizes, and then denormalized this median by multiplying by the mean of the four 75%-points. Finally, where more than one condition involved the same delay

13. In Experiments 3, 4, and 5, which provided the data to which these analyses were applied, each subject was tested with four different array sizes at seven different probe delays, defining 28 size-delay pairs, but some of the delays were examined in more than one experiment, thus defining 48 conditions.

(because of replications across experiments) we obtained the mean over the corresponding values.

It is because the sample variance is especially sensitive to outliers that we applied the median to combine values over subjects, as mentioned above. Where we used the (robust) *MAD* as the dispersion statistic, we applied the mean to combine values over subjects, instead.

11.4 Dispersion as a function of array size and delay

Overall variance Overall variance as a function of array size is shown in Figure 6A for each of the seven probe delays. For the shortest delay (−.05 sec) the function is virtually flat, indicating no effect of array size, consistent with the direct-access property. The same set of data points are plotted as a function of delay in Figure 6B, with array size as the parameter; here there is a suggestion that each function has one (or possibly more) peaks, and that the (first) peak is found at a delay that increases with array size. Qualitatively this pattern is consistent with a probability mixture in which the mixing probability changes more rapidly for smaller arrays; clearly a quantitative test is called for. (See Appendix 1 for a discussion of the variance of a mixture, and Section 17 for the application of such a quantitative test.)

Corresponding values based on the square of the *MAD* are shown in Figures 7A and 7B; agreement between the patterns of results using the sample variance and the *MAD* is remarkably good (up to a multiplicative constant), reinforcing our impressions.

Residuals variance Residuals variance as a function of array size and of delay is shown in Figures 8A and 8B, respectively. Values are substantially smaller than overall variances, as expected. Qualitatively the data patterns are similar, which we find surprising.

12. Parameters of the RT function: Slope

Figure 9 shows the slopes of the fitted lines as a function of probe delay, separated for the six experiments. The slope for Experiment 6 is shown in association with the longest delay we examined--3.45 sec--but note that as no array was displayed and the sequence of spoken digit names was presented at about two digits/sec and hence over an extended interval, we cannot define an equivalent probe delay.

In general, slope values agree well across experiments, but there are two differences that require comment. First, although there appears to be no consistent tendency for slope to decrease with practice, values for Experiment 1 are higher than in the later experiments, possibly a transient associated with relative unfamiliarity with the task.

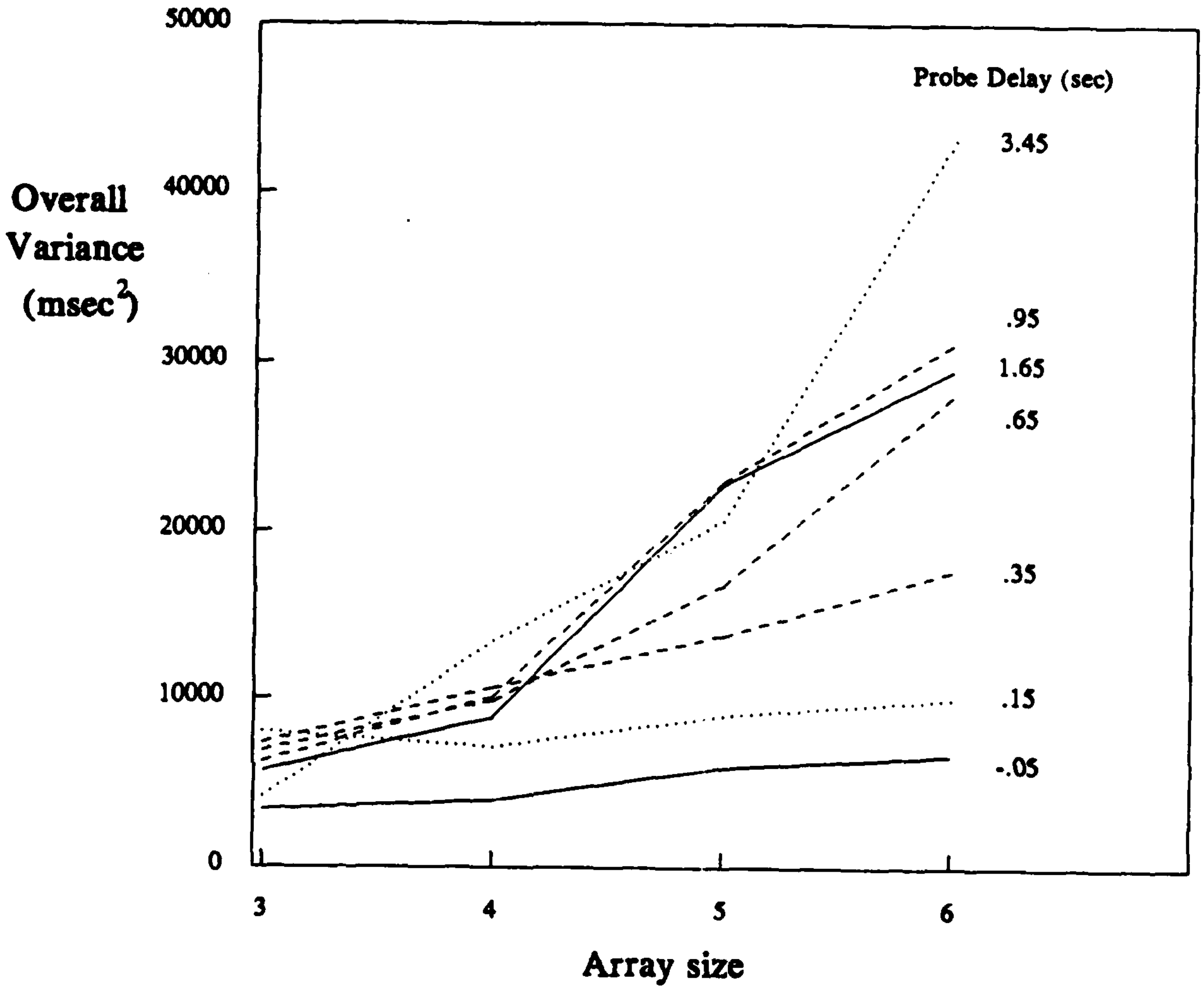
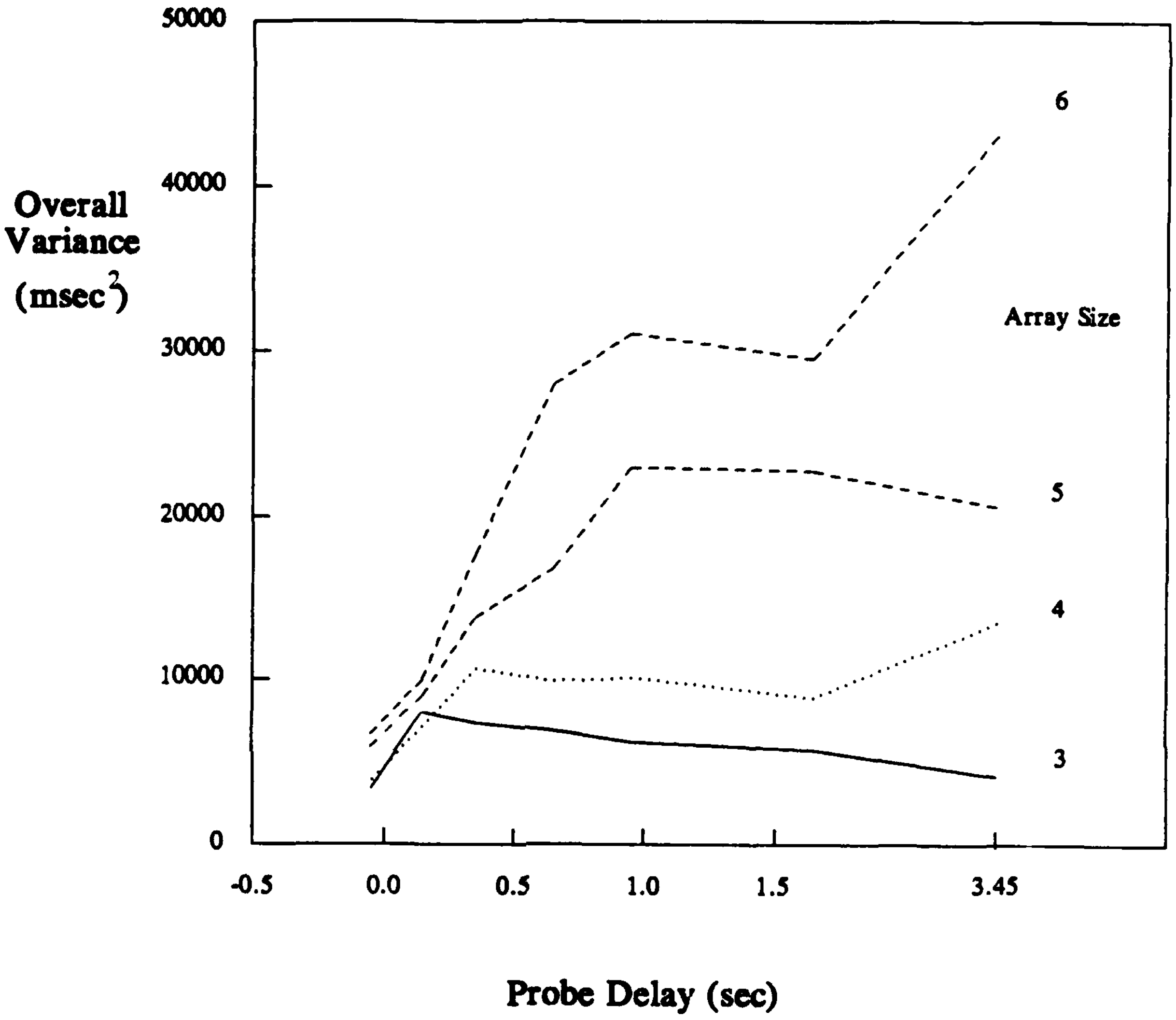

Overall Variance (msec²)
50000
40000
30000
20000
10000
0
Probe Delay (sec)
3.45
.95
1.65
.65
.35
.15
-.05
3
4
5
6
Array size

Figure 6A.



50000
40000
30000
20000
10000
0
Overall Variance (msec²)
6
Array Size
5
4
3
-0.5
0.0
0.5
1.0
1.5
3.45
Probe Delay (sec)

Figure 6B.

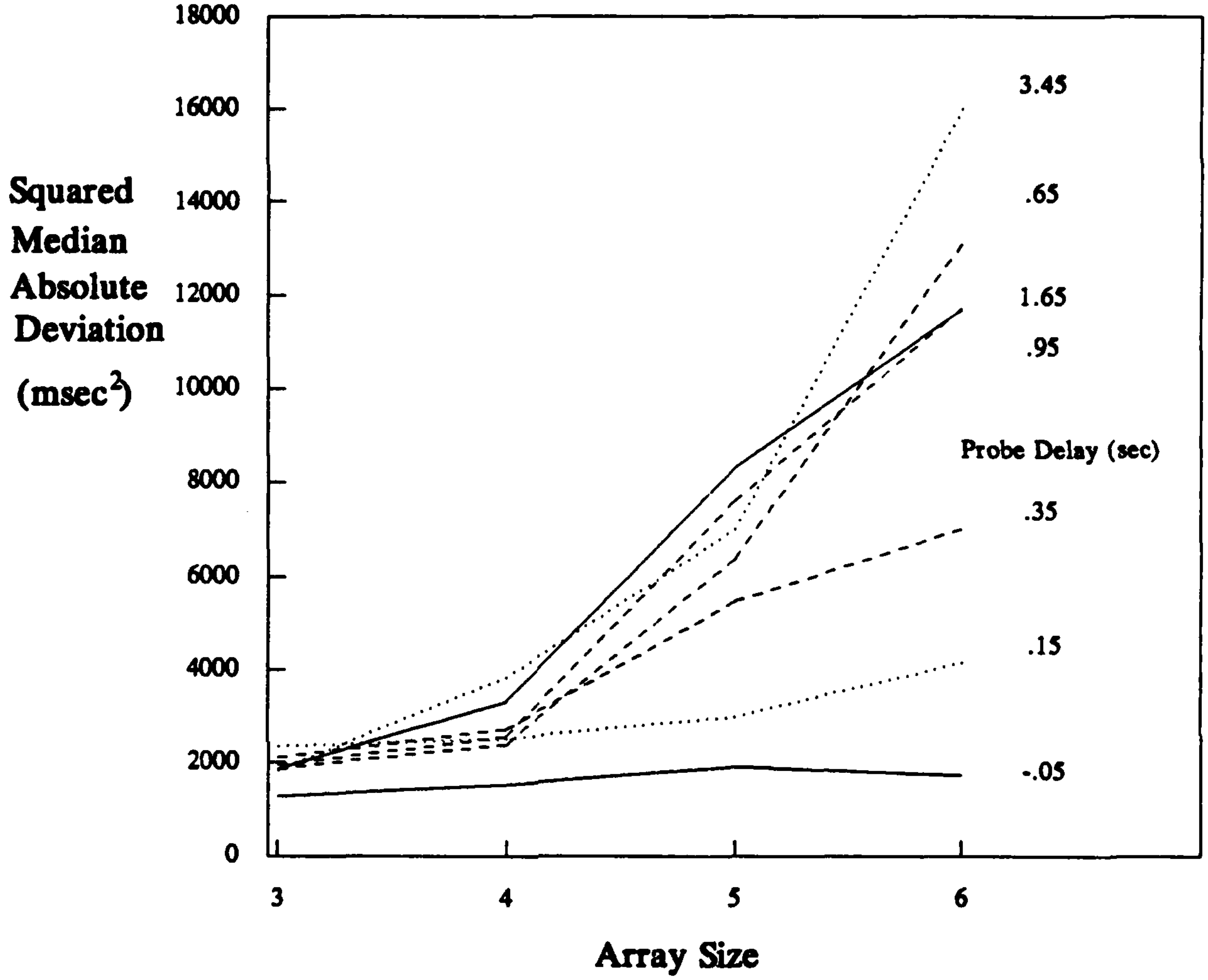

18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Squared
Median
Absolute
Deviation
(msec2)
3
4
5
6
Array Size
3.45
.65
1.65
.95
Probe Delay (sec)
.35
.15
-.05

Figure 7A.

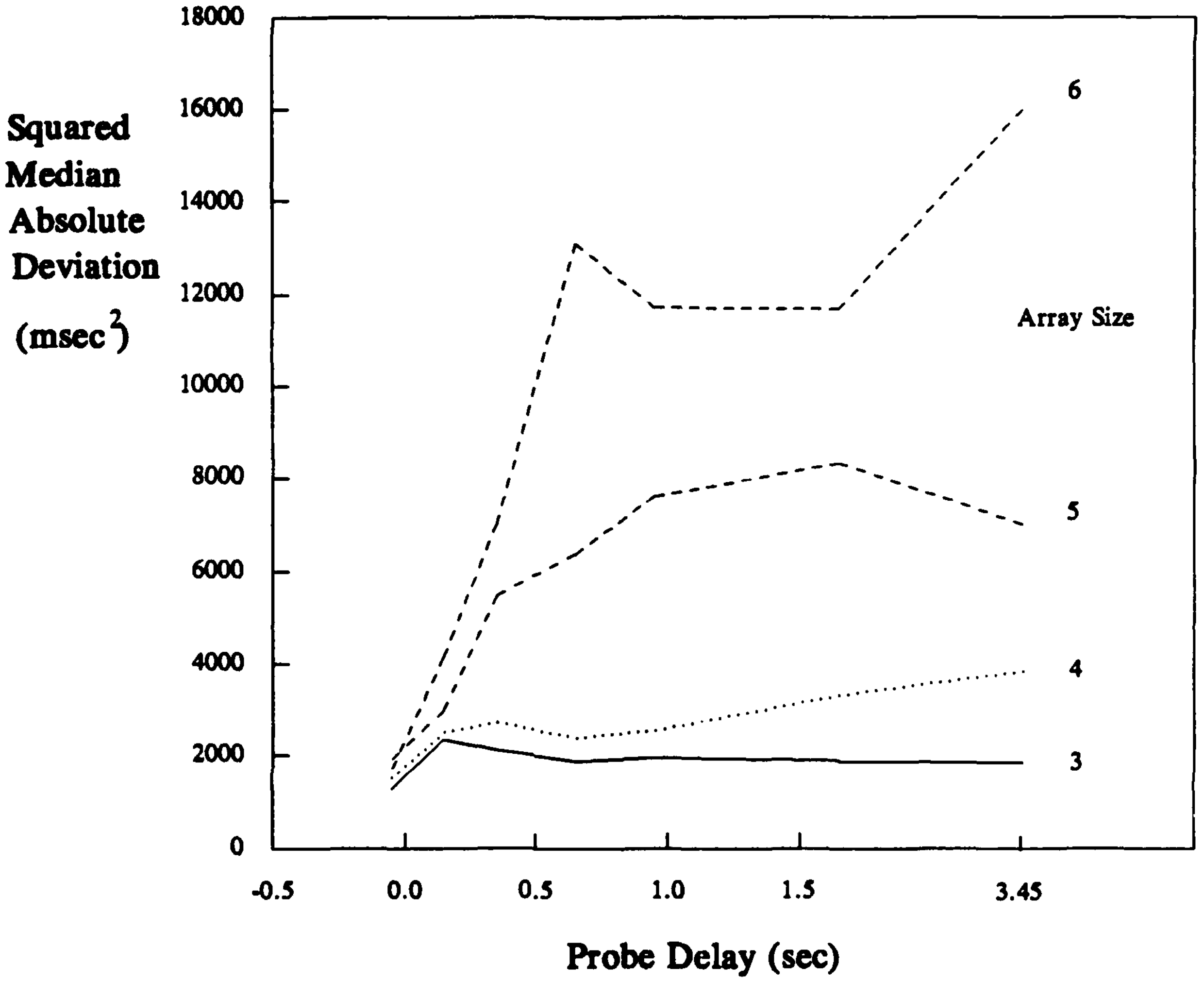

18000
16000
14000
12000
10000
8000
6000
4000
2000
0
Squared
Median
Absolute
Deviation
(msec²)
6
Array Size
5
4
3
-0.5
0.0
0.5
1.0
1.5
3.45
Probe Delay (sec)

Figure 7B.

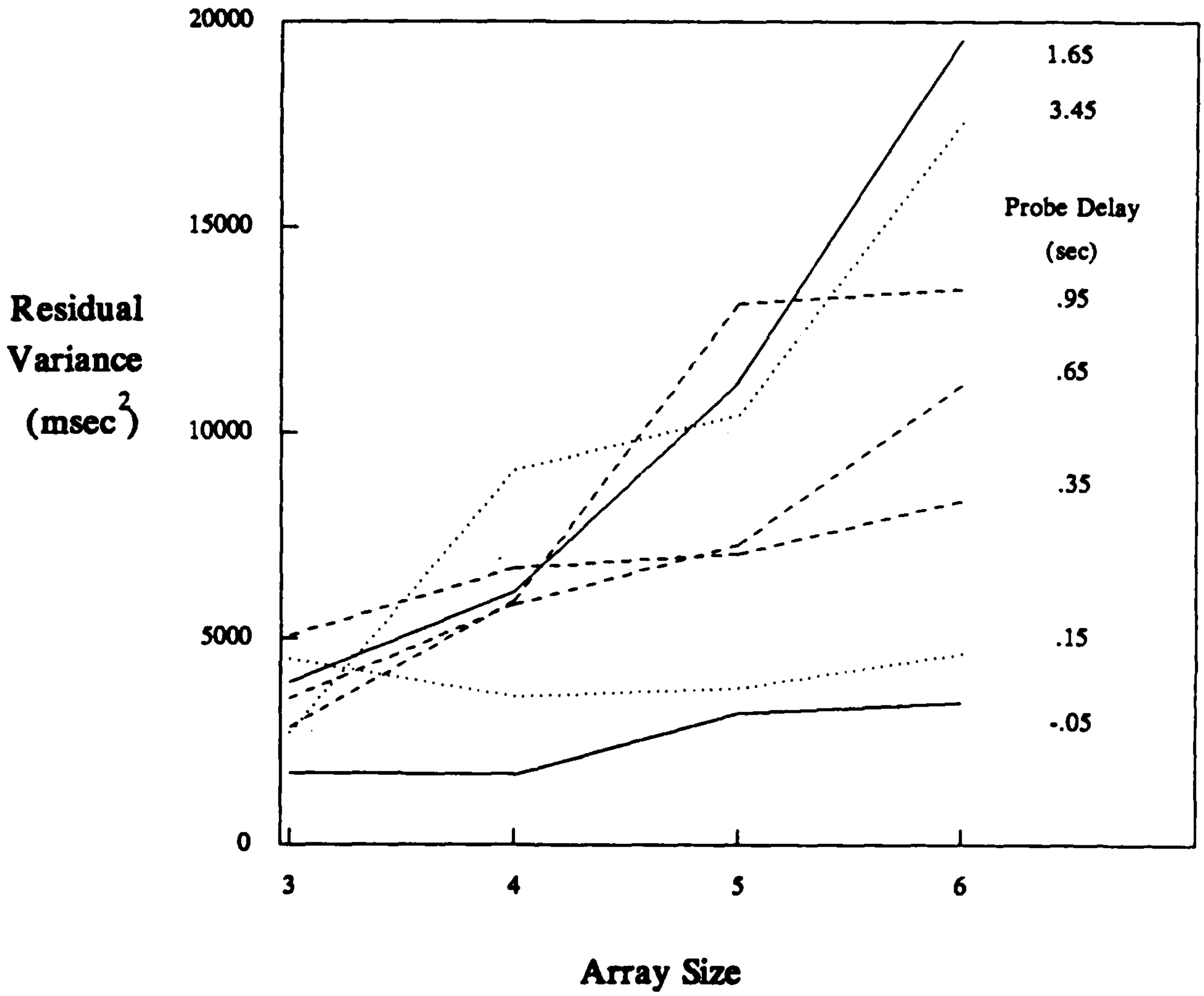

20000
15000
10000
5000
0
Residual
Variance
(msec^2)
3
4
5
6
Array Size
1.65
3.45
Probe Delay
(sec)
.95
.65
.35
.15
-.05

Figure 8A.

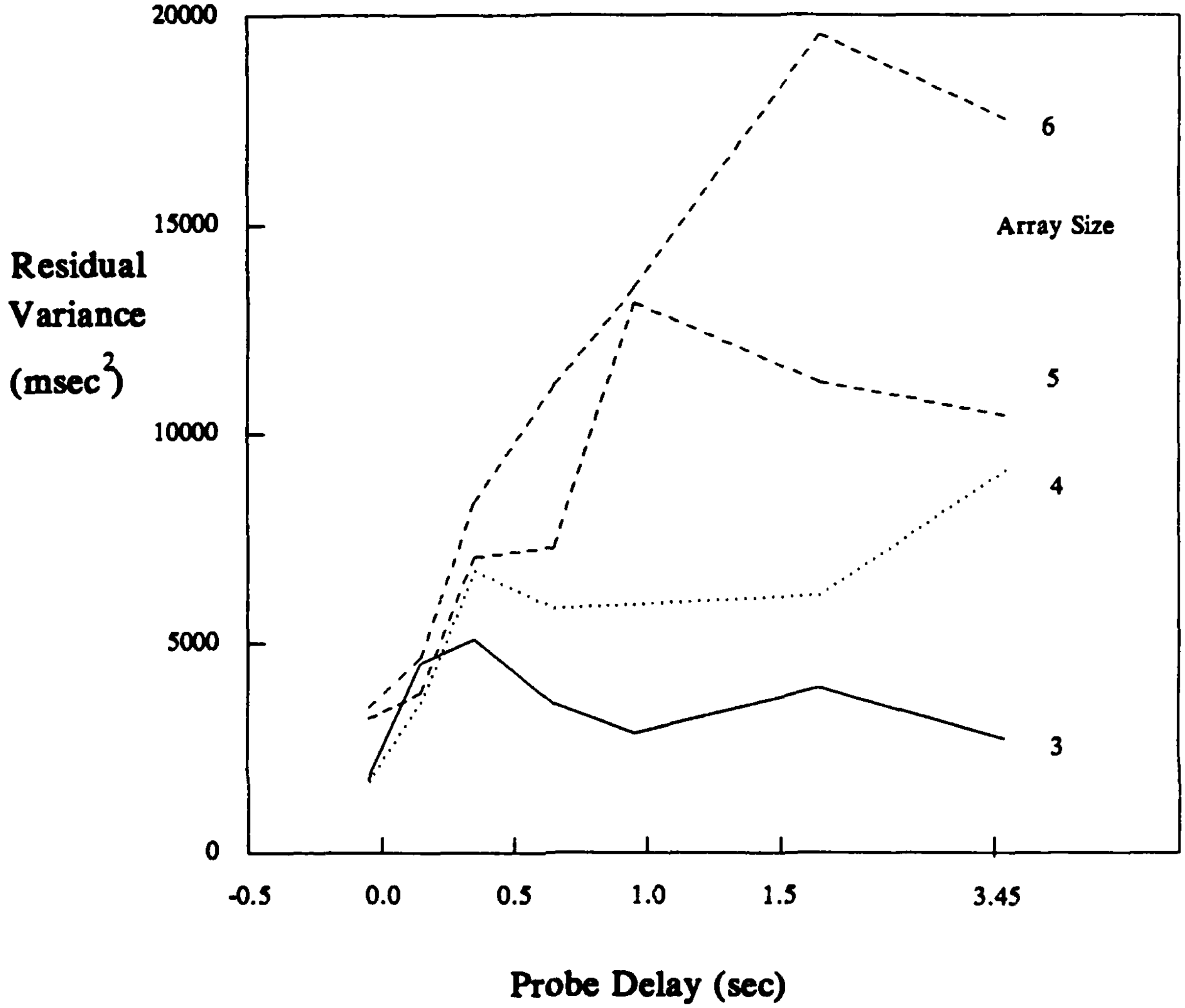

20000
15000
10000
5000
0
Residual
Variance
(msec²)
6
Array Size
5
4
3
-0.5
0.0
0.5
1.0
1.5
3.45
Probe Delay (sec)

Figure 8B.

Second, there may be an effect of context at a probe delay of 0.65 sec. Such an effect is plausible: performance at a particular delay might be influenced by "strategies" that subjects could develop as they are working at other delays. In a region where performance changes rapidly with probe delay a context effect would seem especially likely. (For example, it is conceivable that in a region of rapid transition from one internal representation of the array to another, there might be a delay at which two representations were concurrently available, giving the subject a choice of retrieving the required information from one or the other. This choice might then be influenced by whether she had just been working with relatively short or relatively long delays.) Indeed, in the identity-probe series we found a small (8 msec) but statistically reliable context effect of this kind at the (nominally) "same" probe delay. (See Sternberg, Knoll, & Leuin, 1975, Figure 14.) In the present series the difference between slopes in Experiments 3 and 4 is somewhat larger, but not reliable (15 msec, with an SE--standard error--of 13 msec, based on between-subject variation); the larger slope in Experiment 4 is due primarily to one subject.

Because the differences between slope estimates across experiments appear not to reflect a systematic trend with practice, we summarized our findings by simply averaging these estimates for each delay over those experiments in which that delay was used. We did this for each of the four subjects, and based estimates of the SE on between-subject differences. These means together with 2SE error bars are shown by the ascending curve in Figure 10, where the relevant scale is on the left-hand ordinate; means for each of the four subjects are shown separately in the four panels of Figure 11. As the probe is delayed, the mean slope rises monotonically from a value close to zero to about 90 msec/element; by a probe delay of about 0.65 sec most of the slope increase has been achieved. Note that the variance over subjects, indexed by the SE, also increases substantially with probe delay.

Each subject provided a mean slope at each of eight probe delays. For the full set of data, analysis of variance showed the effect of delay to be highly significant: $F(7,21) = 18.7$. As in the case of the means, we also performed an analysis of slopes for the longest three delays and, in conformity with the findings for means, we found the effect of delay within this set not to be reliable.

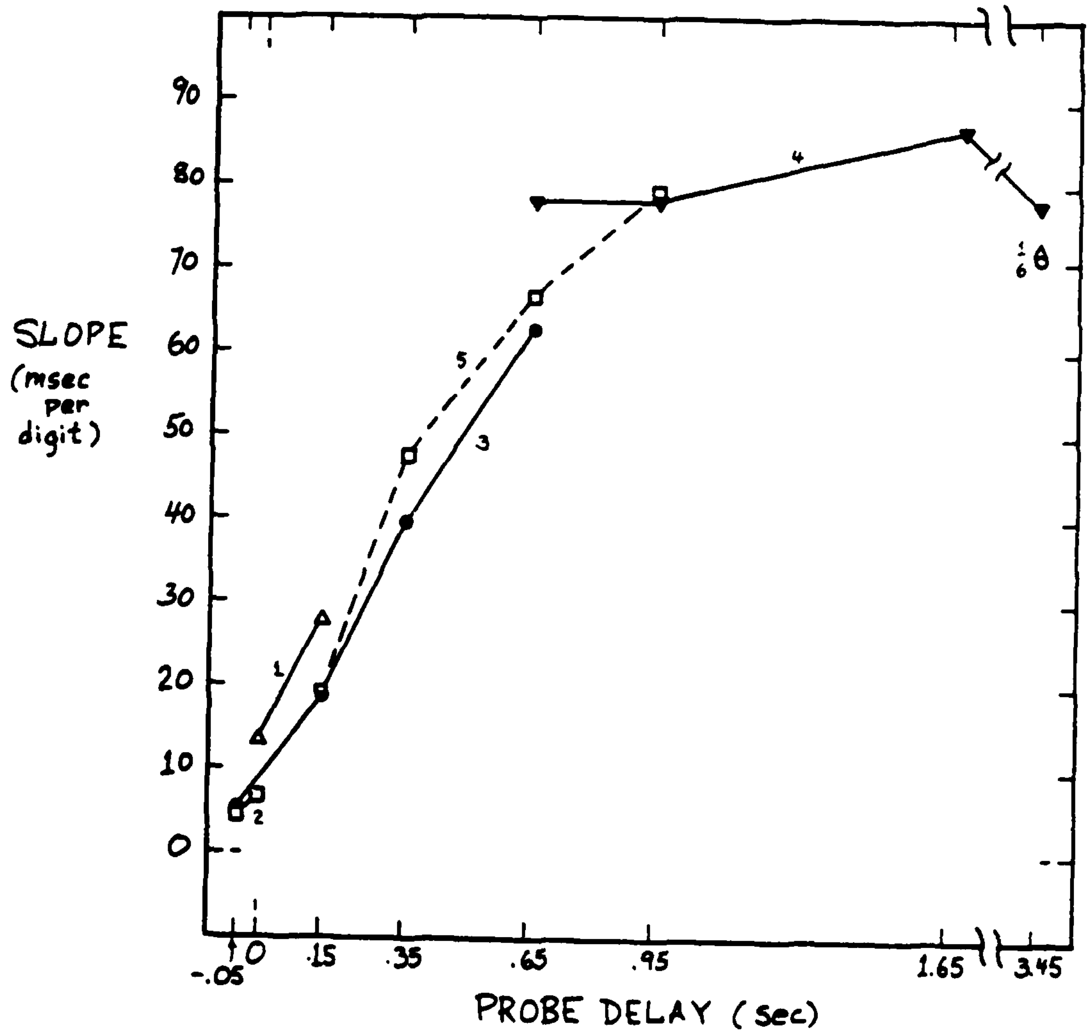

SLOPE
(msec per digit)
90
80
70
60
50
40
30
20
10
0
1
2
3
4
5
6
-.05
0
.15
.35
.65
.95
1.65
3.45
PROBE DELAY (sec)

Figure 9.

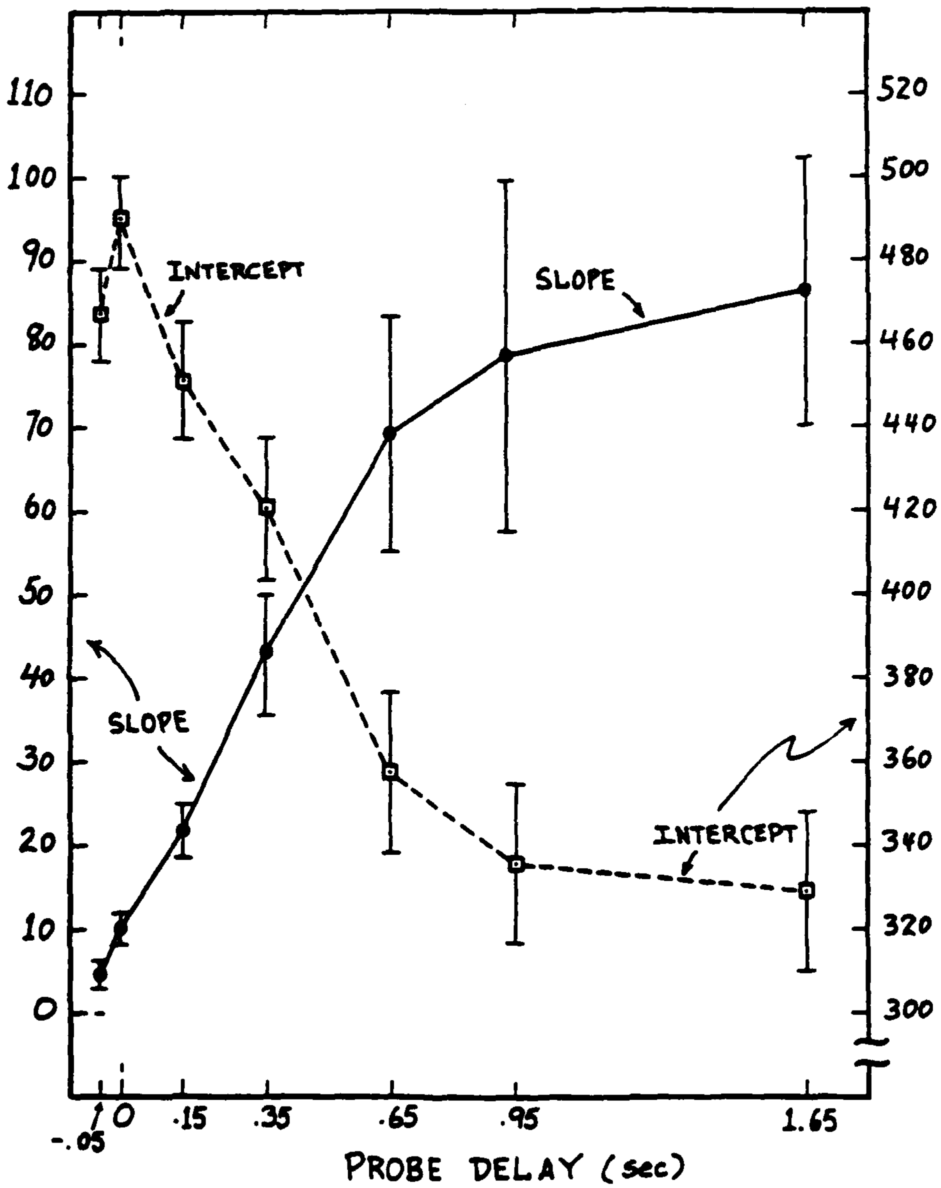

110
100
90
80
70
60
50
40
30
20
10
0
520
500
480
460
440
420
400
380
360
340
320
300
INTERCEPT
SLOPE
SLOPE
INTERCEPT
-.05
0
.15
.35
.65
.95
1.65
PROBE DELAY (sec)

Figure 10.

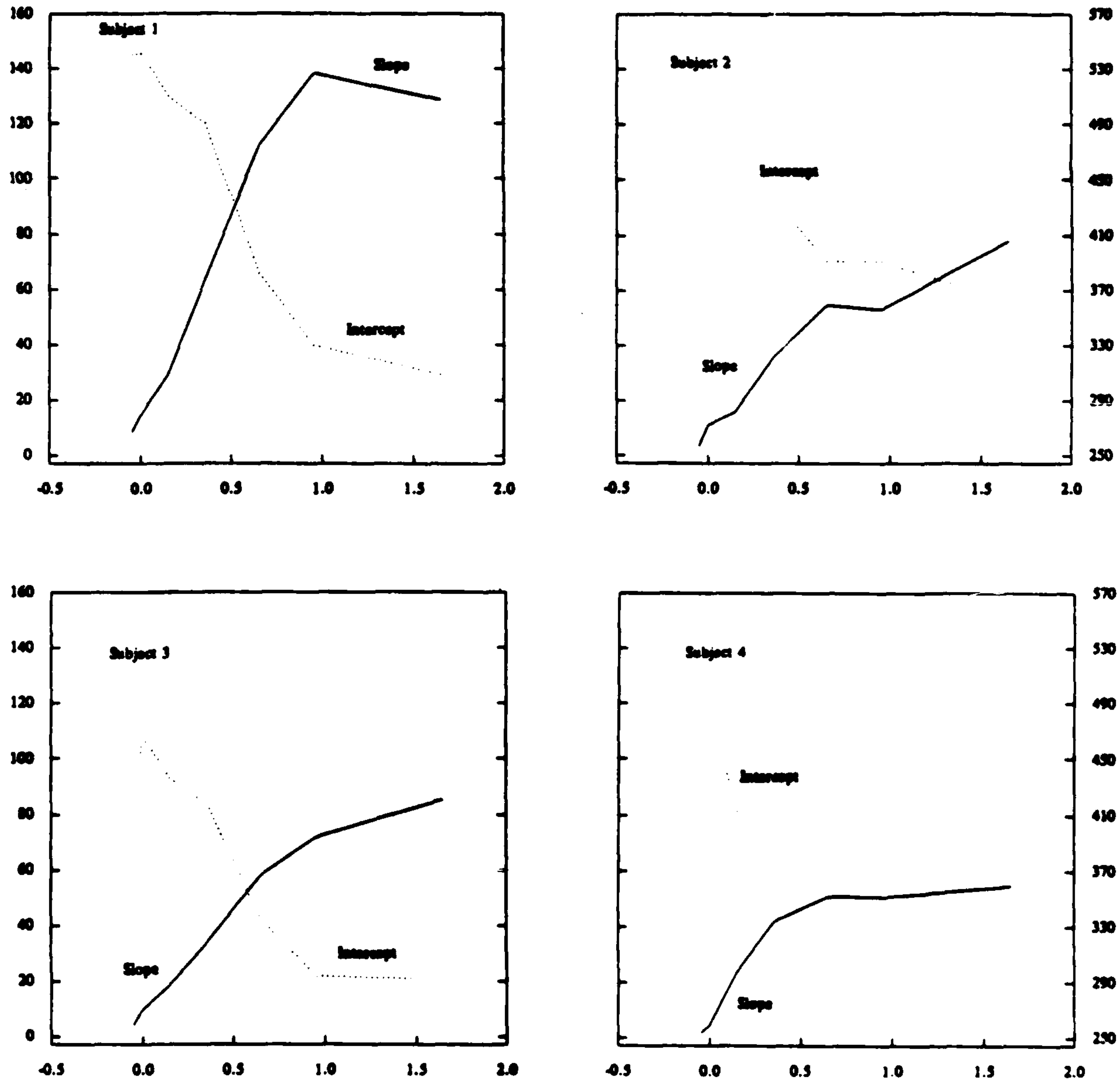

Subject 1
Slope
Intercept
Subject 2
Intercept
Slope
Subject 3
Intercept
Slope
Subject 4
Intercept
Slope
160
140
120
100
80
60
40
20
0
570
530
490
450
410
370
330
290
250
-0.5
0.0
0.5
1.0
1.5
2.0

Figure 11.

13. Parameters of the RT function: Intercept

To characterize the RT function we must specify its height as well as its slope; we do so by using the value of the fitted function at a specified value of s. We chose the 2-intercept ($s = 2$) for reasons discussed below. Before estimating such values we had to combine the several RT functions we obtained at each delay, adjusting for the observed systematic effect of practice (represented by experiment number) on the heights of these functions.

13.1 Adjustment for practice effect

Let us regard the RT as being composed of the durations of a sequence of mental and other operations, all of which might be susceptible to practice effects. We can divide these operations into three classes: (a) those whose durations are influenced by array size (some of which may also be influenced by probe delay), (b) those whose durations are influenced by probe delay but not array size, and (c) those whose durations are influenced by neither. In adjusting for the effects of practice, we consider only changes between one entire experiment and the next, and because only a subset of the probe delays is used in each experiment, we have attempted to adjust only for those effects that are independent of probe delay, and hence probably only those effects that reside in operations of class (c). Effects of practice on the other classes of operation are likely to interact with probe delay, simply because probe delay influences those classes.

For each of Experiments 1 through 4 we estimated the effect of practice from that experiment to the next: we used the RT functions for those probe delays that the two successive experiments included in common, determining the means of these functions over array size together with the difference between these means. We then corrected for this practice effect by using this difference as an additive adjustment constant. (The sum of the adjustments from Experiment 1 to 5 was 75.2 msec.[14]) After making these adjustments, we averaged the RT functions for each probe delay across the experiments that included that delay. The purpose of making the corrections was to have an estimate of the height of the RT function for each probe delay that was not biased by the levels of practice for the subset of experiments in which that delay happened to be included.

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14. An alternative approach would be to perform a multiple linear regression of mean RT on probe delay and experiment number; we would then base the adjustment on the estimated effect associated with experiment number.

13.2 Effect of array size on height of the RT function

We describe the behavior of the 2-intercept in the present section, and explain our choice of this intercept as a measure of height of the RT function in Section 13.3.

The descending curve in Figure 10 shows the mean value of the 2-intercept as a function of probe delay, together with bars denoting 2SE, with the scale for intercept on the right-hand ordinate; means for each of the four subjects are shown separately in the four panels of Figure 11. Note that there is a small but reliable nonmonotonicity between delays of -50 msec and zero: the intercept value is either "too great" at delay zero, or "too small" at delay -50. Except for this the intercept declines by about 150 msec over the range of probe delays we investigated, with most of the reduction having been achieved by about 0.65 sec. The time course of this intercept change is thus similar to that of the slope. In Section 15 we approach the comparison of time courses with a more precise method, and discuss reasons why the nonmonotonicity mentioned above may be uninterpretable.

13.3 Choice of intercept of the RT function

In this section we explain our choice of the 2-intercept. We begin by regarding the mean $RT = T(s,t)$ at probe delay t as being composed of the durations of two sets of processes, one set influenced by array size, s, the other not so influenced. Let A represent the sum of durations of the uninfluenced set, and B represent the corresponding sum for the influenced set. Since both may also be influenced by probe delay we write

$$T(s,t) = A(t) + B(s,t). \quad (13.1)$$

Our goal in selecting an intercept is to have an estimate of the duration, $A(t)$, of processes not influenced by array size. Our interest in this decomposition is generated by the observation that both A and B are influenced greatly by probe delay; that is, we have two facts about probe delay that require explanation. Moreover, given permissible decompositions, the influences are in opposite directions: Whereas B rises with t, A falls.

To make this clear, let us consider the set of permissible decompositions. The choice is less arbitrary than it would seem, even without a specific model of the process that generates the array-size effect. First, consider a particular value of t. Within the domain of s examined in most experiments $T(s,t)$ is (approximately) linear in s. This implies that if we extrapolate the s-domain in both positive and negative directions, then any possible decomposition can be obtained by choosing a value of $s = s'$ and defining

$$A'(t) = T(s',t) \quad , \tag{13.2}$$

which also defines

$$B'(s,t) = T(s,t) - T(s',t) \quad . \tag{13.3}$$

Now we express the empirical data, which obey a linear law, by

$$T(s,t) = \alpha_0(t) + \beta(t)s \quad . \tag{13.4}$$

(We give $\alpha_0(t)$ the subscript zero to indicate that it is the zero intercept of the empirical fitted function.) We then have

$$A'(t) = \alpha_0(t) + \beta(t)s' \quad , \tag{13.5}$$

and

$$B'(s,t) = \beta(t)(s - s') \quad . \tag{13.6}$$

Under conditions where s has an effect, the quantity $(s-s')$ can be interpreted as being proportional to the mean number of operations, $k(s-s')$, each with mean duration $\beta(t) / k$, carried out by processes influenced by array size. Now we add the assumption that this mean number is independent of t. This implies that the decomposition (specified by s') that obtains for a particular t also obtains for all other t.

Next, we obtain an upper bound on s' by noting that as both A and B represent process durations, neither may be negative. This constraint and Equation 13.6, together with the empirical observation that

$$\beta(t) \geq 0 \quad , \quad (\text{all } t) \quad , \tag{13.7}$$

requires that

$$s - s' \geq 0 \quad , \tag{13.8}$$

or

$$s' \leq s \tag{13.9}$$

for all admissible s-values.

Now, an s-value is admissible if we know or expect that it will fall within the range of the linear law. In the present series of experiments the smallest s-value used was $s = 3$. But recall that the leftmost array element was never probed; thus one can argue that the effective array size was $s-1$. Furthermore, in another experiment, where *all* array elements could be probed, we let s take on values $2 \leq s \leq 6$ and found a linear law applying to the full range.[15] Finally, in still another experiment we have found that $T(1,t)$ falls below a line fitted to the values of $T(s,t)$ for $s \geq 2$; this was not unexpected, as (a) $s = 1$ permits the subject to prepare her response in the absence of the marker, (b) the discrimination of marker location is not required before initiating the response, and (c) the element to be named is distinguished from elements in all other conditions by being an *isolated element* -- i.e., having no neighbors. (See Section 6.1.)

We conclude that the range of admissible s-values includes $s = 2$ (and probably excludes $s = 1$), which in turn imposes the requirement $s' \leq 2$ (when all elements may be probed), or $s' \leq 3$ (in the present series of experiments, where the leftmost element was never probed and, hence, where it may not have participated in the operations whose durations we are considering).

By examining Equations 13.5 and 13.6 we see that for either of the above constraints on s' we have support for the claim that increasing probe delay causes A' and B' to change in opposite directions: For our data, $\beta(t)$ is increasing in t; given the constraint on s', so is $B'(s,t)$ at all admissible s-values. On the other hand, $A'(t)$ is the s'-intercept, and it is clear from the data that for $s' \leq 3$ it is decreasing in t.

13.4 Implications of the choice of intercept for time-course comparison

One question of importance is whether the time courses of changes in intercept and slope are the same. If so, it is tempting to search for a common mechanism that they might both reflect; if not, we may have to consider at least two separate mechanisms, both influenced by probe delay.[16] In choosing a decomposition, then, it is important to consider whether it is likely to seriously mislead us on this point.

Suppose that the correct decomposition is associated with s', but we use s'' instead. What is the consequence? Instead of $A'(s,t)$ and $B'(s,t)$, we have

15. This experiment was summarized as Experiment 7 in Sternberg, Knoll, & Turock, 1985, and will be described in more detail in a forthcoming report.

16. By a "time course" we mean the function of time given by the proportion of the change that will ultimately occur that has already occurred by a specified probe delay; see Section 15. Because the time course of the change in some attribute of a linear function depends on how the function is parameterized, caution is needed in interpretation. Thus, in general, any nonlinear transformation of a changing parameter will alter its time course. Indeed, similarity or identity of time courses may be a criterion for choosing one of several descriptions as more fundamental.

$$A''(t) = A'(t) + (s'' - s')\beta(t) \quad , \tag{13.10}$$

and

$$B''(s,t) = B'(s,t) - (s'' - s')\beta(t) \quad . \tag{13.11}$$

The time course of the change in B is unaffected, as the changes with t in both B' and B'' depend entirely on the change in β. However, if A' and B' have different time courses, then A'' will be a composite, the sum of two terms with different time courses. This composite will then have a time course that differs from that of either constituent. It follows that if A' and B' have different time courses, then so will A'' and B''. On the other hand, if A' and B' have the same time course, then so will A'' and B''. The sensitivity of any such comparison to time-course differences will probably be greater insofar as A is less contaminated by "part" of B. For this reason and others it is desirable to aim for a theoretically justifiable decomposition.

14. Some models of the array-size effect and its change with probe delay.

In interpreting the effects of delay on A and B, it is helpful to consider some specific models of the array-size effect and its change with probe delay. We discuss several simple models below, in the spirit of illuminating some possibilities, and not because we feel we have much evidence favoring one model over another. The models we discuss in this section all involve serial search, with a mean search time per element (or per location) that is independent of array size; Such a process is in turn suggested by the persistent linearity of the RT functions.

In all three models, we assume that if and when search takes place, it is accomplished by means of a self-terminating series of tests through a set of elements (the search set) that determines for each element tested whether its location is the one probed. (One possibility is that each element has a location attribute or "tag," and that the test of an element determines whether its location attribute is the attribute sought.) We assume, further, that because the leftmost array location is never probed in the present series of experiments, that location is never tested. For an array of s elements, the search set contains $s-1$ elements; the total number of elements tested then ranges from 1 through $s-1$, with the final test leading to a "match," the others leading to mismatches. Thus it is by means of its influence on the number of mismatches that array size has its effect.

14.1 Model 1: Self-terminating search with increasing mismatch duration.

Let the mean durations of matching and mismatching tests be $\beta_m(t)$ and $\beta_{mm}(t)$, respectively. We write the test durations as functions of probe delay in this model, because it is an increasing mismatch duration that produces the increasing array-size effect with probe delay. One possibility is to regard $\beta_{mm}(t)$ as the mean delay between the beginning of the test of one element and the beginning of the test of another. A small value of $\beta_{mm}(t)$ could then reflect greater temporal overlap of tests whose intrinsic mean duration is invariant with probe delay, and a zero value could indicate fully parallel testing. "Direct access" would then perhaps be more properly described as "parallel access."

Whatever the order of search, the (random) distribution of probe locations causes the matching test to be at a random position in that search. Thus half of the nontargets in the search set are actually tested, on average: The mean number of mismatching tests before the match is the mean of 0, 1, 2, ... $s-2$, or $(s-2)\ /\ 2$. We thus have

$$B(s,t) = (s-2)\beta_{mm}(t)\ /\ 2\ , \qquad (14.1)$$

and we note that $\beta_m(t)$ is incorporated in $A(t)$. This gives us

$$T(s,t) = A(t) + (s-2)\beta_{mm}(t)\ /\ 2\ ; \qquad (14.2)$$

thus

$$T(2,t) = A(t)\ , \qquad (14.3)$$

so that the 2-intercept provides an estimate of $A(t)$, and includes none of the time for mismatches, as desired. The slope of the reaction-time function is $\beta_{mm}(t)\ /\ 2$; changes with probe delay in this slope reflect changes in $\beta_{mm}(t)$, which is the mean time per mismatch (given a serial model), or the mean additional time per mismatch (given a model with overlapping tests).

14.2 Model 2: Increasing probability of searching entire array.

Suppose at any given delay there is a mixture of two kinds of trials. On direct access trials, which occur with a probability $p(t)$ that is independent of s and declines with probe delay, the probed element can be retrieved by direct access; we assume this process to have a fixed mean duration D. On search trials, which occur with probability $1 - p(t)$, all elements in the array (except the leftmost) are tested in a self-terminating manner, with each test determining for an element whether it has the desired location attribute. Unlike Model 1, we assume here that the search times per element (β_m and β_{mm}) are independent of probe delay. When search is used, the mean number of mismatches is the mean of $0, 1, \ldots, s-2$, or $(s-2) / 2$. We thus have

$$T(s,t) = A(t) + p(t)D + [1-p(t)](s-2)\beta_{mm} / 2 \ . \qquad (14.4)$$

Note that the term associated with the matching test, $[1-p(t)]\beta_m$, is again incorporated in $A(t)$. The 2-intercept, $T(2,t) = A(t) + p(t)D$ includes none of the time for mismatches, as desired; the slope is $[1-p(t)]\beta_{mm} / 2$, which starts at zero $[p(t) = 1]$ and grows towards $\beta_m / 2$ as $p(t)$ declines towards zero.

14.3 Model 3: Search through an increasing proportion of array elements.

For each element there is a delay-dependent probability $p(t)$, independent of s, that it can be directly accessed by location; otherwise search must be used. As in Model 2 the time increment per element when search occurs is independent of probe delay. In addition to the target element the search set then includes just those of the remaining $s-2$ elements *not* susceptible to direct access (rather than all the elements, as in Model 2). The number of these is binomially distributed, $b[s-2;1-p(t)]$. The mean number of nontargets in the search set is therefore $[1-p(t)](s-2)$; a mean of half of these is actually tested, to generate mismatches, before the match occurs. We then have

$$T(s,t) = A(t) + p(t)D + [1-p(t)][(s-2)\beta_{mm} [1-p(t)] / 2] \qquad (14.5)$$

or

$$T(s,t) = A(t) + p(t)D + [1-p(t)]^2 (s-2) \beta_{mm} / 2 \ . \qquad (14.6)$$

The term associated with the matching test is the same as in Model 2, and is again incorporated in $A(t)$. The 2-intercept is the same as in Model 2; the slope is the same except that $[1-p(t)]^2$ replaces $[1-p(t)]$; again, the slope grows as $p(t)$ declines. Because $p(t)$ appears in a squared term with the slope, but linearly in the intercept, time courses for slope and intercept would differ, although the changes should begin and should "reach" asymptote at the same delays. This is an instance where a time-course difference between slope and intercept does not call for two separate mechanisms, however; caution is suggested in drawing inferences from such a difference.

Three additional models are generated if we assume that if and when a search occurs in each of the above models, it is exhaustive rather than self-terminating. If so, the number of mismatching tests is equal to the number of nontargets in the search set, rather than half that number, causing a doubling of the slopes given above, but otherwise the equations for mean RT remain the same.

If we relax the assumption that in the present series of experiments the leftmost element is not included in any search, then we may have conditions under which the 2-intercept is inappropriate. In that case, the equations for all three models as well as their exhaustive-search variants must be altered, replacing $s-2$ by $s-1$. It follows that the intercept desired is the 1-intercept instead of the 2-intercept; if we use the 2-intercept, then we obtain an estimate of the sum $A(t) + \beta_{mm}$ rather than the desired $A(t)$. Because only in Model 1 does β_{mm} depend on probe delay rather than being a constant, this is of concern in relation to comparing the time course of change only in that model. But even here, if the sum changes with t with the same time course as one of its components $[\beta_{mm}(t)]$, then so must $A(t)$ alone, if it changes at all.

15. Time course of slope change and intercept change compared

Regard the slope (β) and a selected intercept (α; for present purposes we suppress the subscript k) of the RT function as functions of probe delay t over a domain $t_1 \leq t \leq t_n$: $\beta(t)$, $\alpha(t)$. There are at least two senses in which the time courses of the two parameters can be compared. The first (weak) comparison is in terms of starting and ending points: Do the two parameters start and stop changing at the same values of probe delay? It is clear from Figures 12 and 13 that it would be difficult to reject an affirmative answer, but it is also clear that a precise determination is difficult because, although the changes may start abruptly, they end gradually. Subject to this statistical proviso, then, we can assert that we have *weak time-course identity.*

To consider a stronger sense of time-course comparison we must develop some additional terminology. Let $p_\alpha(t)$ and $p_\beta(t)$ be the time course functions for α and β, respectively, giving the proportion of the total change in each parameter from t_1 to t_n that has been achieved at probe delay t. Define the parameter values at the endpoints of the domain as α_1, α_n, β_1, and β_n. We then have

$$\alpha(t) = \alpha_1 + (\alpha_n - \alpha_1)p_\alpha(t), \tag{15.1}$$

and

$$\beta(t) = \beta_1 + (\beta_n - \beta_1)p_\beta(t) \tag{15.2}$$

Note that by definition, $p_\alpha(t_1) = p_\beta(t_1) = 0$, and $p_\alpha(t_n) = p_\beta(t_n) = 1$. This does not necessarily reflect the weak identity property, since (t_1, t_n) need not exhaust the domain over which the parameters change.

We now suppose a *strong time-course identity*: $p_\alpha(t) \equiv p_\beta(t) = p(t)$. Now when we eliminate $p(t)$ from Equations 15.1 and 15.2, we find (assuming that $\beta_n - \beta_1 \neq 0$)

$$\alpha(t) = \frac{\beta_n\alpha_1 - \beta_1\alpha_n}{\beta_n - \beta_1} + \frac{\alpha_n - \alpha_1}{\beta_n - \beta_1}\beta(t). \tag{15.3}$$

Thus, strong time-course identity over a domain $t_1 \leq t \leq t_n$ implies that $\alpha(t)$ is a linear function of $\beta(t)$ over that domain. One test of the property, then, is to evaluate the linearity of the plot of α_i against β_i, where the subscripts now index all or some of the (finite) set of n time delays $\{t_i\}$ used in an experiment.

One convenient formulation of such an analysis arises if we normalize the parameter values as follows:

$$a(t) = \frac{\alpha(t) - \alpha_1}{\alpha_n - \alpha_1}, \tag{15.4}$$

$$b(t) = \frac{\beta(t) - \beta_1}{\beta_n - \beta_1} \tag{15.5}$$

Then $a(t) = p_\alpha(t)$, $b(t) = p_\beta(t)$, $a(t_1) = b(t_1) = 0$, and $a(t_n) = b(t_n) = 1$, so over the domain of t-values, $a(t)$ is a linear function of $b(t)$ that passes through the points (0,0) and (1,1). For the finite set of sample values at the delays $\{t_i\}$ we then evaluate the linearity of such a plot of a_i against b_i .

To interpret such plots of sample values it is useful to consider consequences of failure of the hypothesis of strong time-course identity. Suppose that $p_\alpha(t) \neq p_\beta(t)$. Because their definition requires $p_\alpha(t_1) = p_\beta(t_1) = 0$ and $p_\alpha(t_n) = p_\beta(t_n) = 1$, a power-function relationship captures many of the plausible discrepancies:

$$p_\alpha(t) = [p_\beta(t)]^\delta. \tag{15.6}$$

It follows that $a_i = b_i^\delta$. For the range $0.7 \leq \delta \leq 1.3$, the largest deviation between b_i^δ (unequal time courses) and b_i (equal time courses) is observed at $b_i \approx 0.35$. When $b_i = 0.35$ the deviations for $\delta = 0.7$, 0.9, 1.1, and 1.3 are 0.13, 0.04, −0.03, and −0.09, respectively. Assuming that we can detect a deviation of about 10% of the b_i range, the method would thus appear to be sensitive to deviations $|\delta - 1|$ in δ of 0.3 or more, clearly enough sensitivity, for example, to detect the time-course difference discussed in relation to Model 3 in Section 14.

In applying this method we must first consider the set of probe delays for which it is appropriate. Recall that for the one negative probe delay in this series of experiments (−50 msec) we measured reaction time from the onset of the array, rather than from the onset of the probe as we did for non-negative delays. This is an arbitrary choice -- a crude attempt to adjust our measure such that it assigns the time origin to the earliest point at which information in both array and probe become available, plus an unknown additive constant (which is the same at all probe delays). Because of the arbitrariness of this assignment, we cannot use the intercept value at a probe delay of -50 msec in evaluating the time-course identity of slope and intercept. There may also be reason to be suspicious of the intercept value when the onsets of array and probe are simultaneous: There may be competition between the processes that extract information from array and probe that slows one or both of these processes when they must operate on simultaneous stimuli, and that therefore increases the value of the (unknown) additive constant by some amount, inflating the estimated intercept value when probe delay is zero.

Figure 12 is a plot of α_i versus β_i , where parameter values are those shown in Figure 7. The line is fitted by least squares regression of α on β to data from eight probe delays. Figure 13 shows corresponding plots of α_i versus β_i separately for each of the four subjects, with values being those shown in Figure 8.

Our findings provide moderately convincing support for strong time-course identity. If other data further strengthened this conclusion we believe it would have powerful implications for the nature of the transformation process. Consider what such time-course identity might mean. The slope reflects the duration of processes sensitive to array size, and whereas the intercept may reflect those to some degree, as discussed in Section 13, it also reflects processes whose durations are independent of array size. One possibility, for example, is that the slope may reflect the rate of a process of search, or successive *location testing*, in which representations of array elements are tested one after another until one is found whose location is the same as the location represented by the probe. As the transformation proceeds, then, the mean time increment required by each such test, and measured by the slope, grows. (An increment of zero might correspond either to the absence of such tests, or to such tests being carried out in parallel; if the property of selective processing at a location, discussed in Section 3.4, obtained, this would constitute an argument against the parallel testing alternative.) On the other hand, the intercept may reflect in part a process of *name conversion* -- the time needed to convert the representation disclosed by the search into a spoken name, a process that occurs just once per trial, and whose duration is independent of array size. As the transformation proceeds, then, the representations of elements in the array change such that the mean time to perform this conversion is reduced.

Now suppose that we had precise descriptions of each of these processes -- location testing and name conversion -- and of how they depended on the progress of the transformation process. It seems quite plausible that the parameters that reflected these two processes would start and stop changing at the same time as the transformation process starts and ends, thus conferring

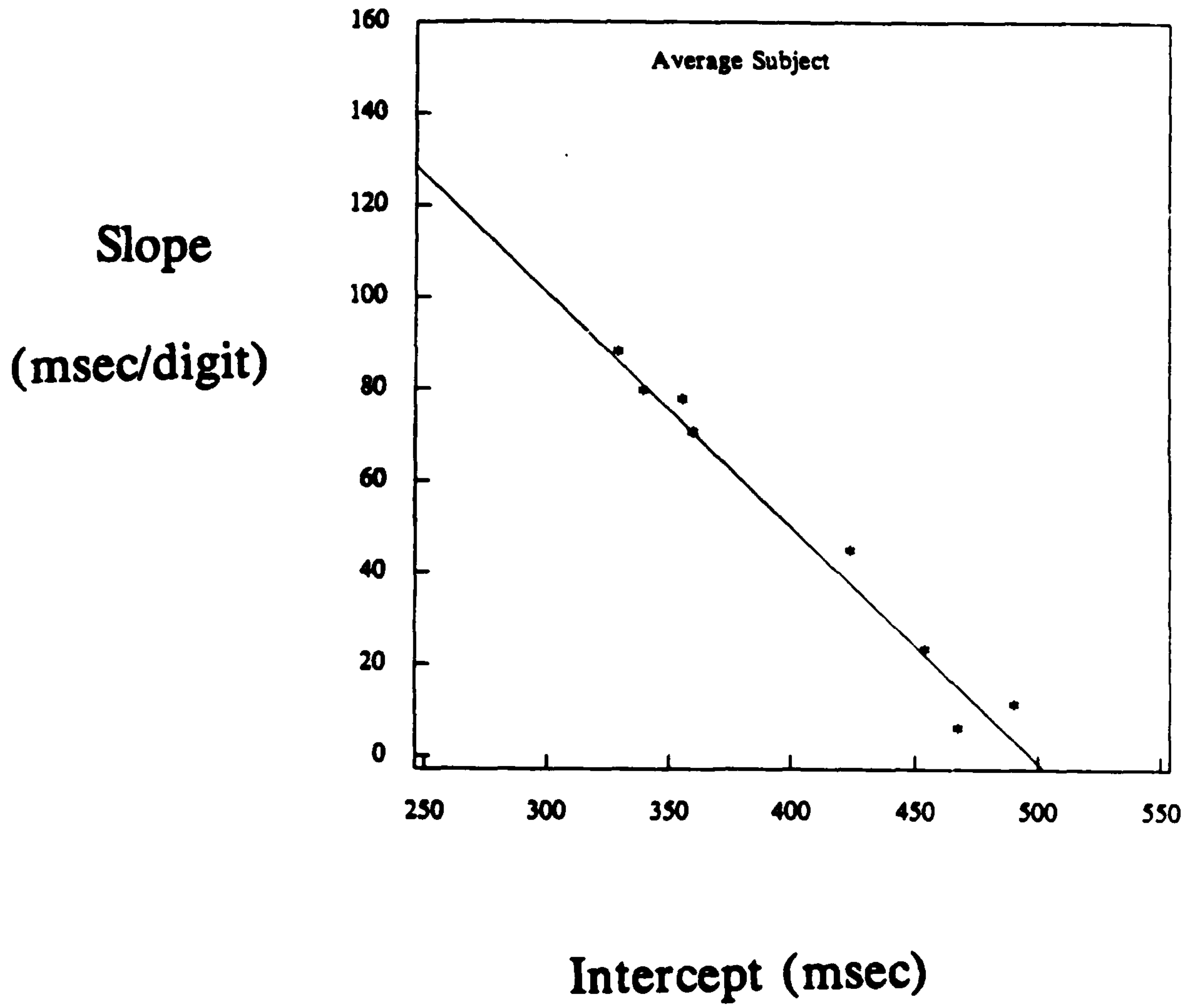

Average Subject
Slope
(msec/digit)
160
140
120
100
80
60
40
20
0
250
300
350
400
450
500
550
Intercept (msec)

Figure 12.

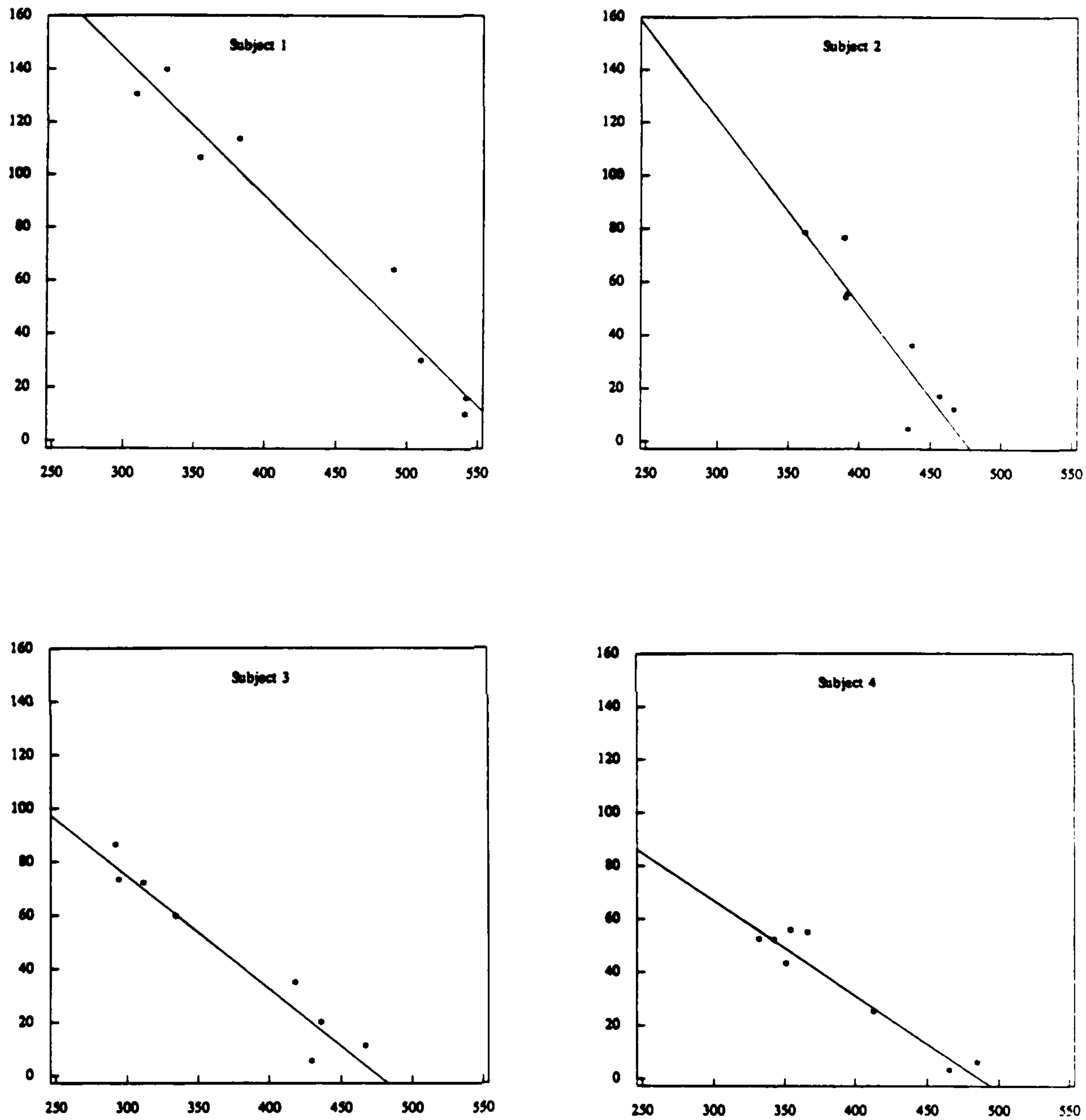

Subject 1
Subject 2
Subject 3
Subject 4
160
140
120
100
80
60
40
20
0
250
300
350
400
450
500
550

Figure 13.

weak time-course identity on the parameters. On the other hand, for such a mechanism to produce strong time-course identity, we would have to believe that for each point in the progress of the transformation the proportional reduction in name conversion time would exactly equal the proportional increase in location-testing time. For a transformation that takes the representation through more than two states, there seems to be no reason to expect this. There is one circumstance, however, under which such equality might be expected. Suppose that what we are observing is a binary probabilistic mixture of two mechanisms, one a direct access mechanism, with a slope close to zero and a relatively large intercept, and the other a search mechanism, with a slope of about 80 msec/element and a relatively small intercept. As the transformation proceeds, the mixing probability changes in a gradual fashion. At any probe delay, the value of each parameter would then be a weighted average of its values at the extreme delays, with the weight given by the mixing probability. The time-course function for each parameter would therefore be the (common) mixing probability, considered as a function of time, and strong time-course identity would fall out very simply. Furthermore, if the two extreme-delay states being mixed each produced linear functions relating mean reaction time to array size, then all functions at intermediate delays would also be linear, as we (approximately) observe. (Among the models of the transformation process that would produce such a mixture is Model 2 of Section 14.) Unfortunately our data also contain evidence against this probabilistic mixture hypothesis, as discussed in Section 17, below.

16. Comparison of time course of slope change for spatial- versus identity-probe data

We explained in Section 7 how we attempted to match the conditions of the present series of experiments with those we used for an earlier series with the same four subjects that employed the identity-probe paradigm. Results from that earler series are detailed in a previous report (Sternberg, Knoll, & Leuin, 1975) and briefly summarized in Section 4. Whereas the responses in these two paradigms are the same (the spoken name of a designated element in the array), the types of information by which they are designated -- spatial location in the new experiments, versus identity of an adjacent element in the earlier ones -- are radically different. In both paradigms, however, we see evidence of a rapid transformation of the internal representation of the array, as indicated by the changing patterns of retrieval times; an initial examination suggests that the time courses of the transformation are remarkably similar. It is tempting to believe that the two sets of data are simply alternative indices of the same underlying transformation. If so, we would expect the time courses of change of the two indices to be identical. To test this expectation we need a method of precise comparison.

The first problem we confront arises from the fact that equal nominal probe delays of spoken name and visual marker probes are not necessarily equivalent in terms of how far an array-transformation process may have progressed. In general we have to add a constant to the physical probe delay in one experiment to develop a correspondence between experiments. How should the additive constant be determined? One possible method is to estimate in each experiment that probe delay at which the transformation starts, and adjust the probe delays so as to align these starting points. A second method is to find the alignment that minimizes the disagreement between time-course functions. For either method, we must use interpolation in the data from (at least) one experiment to obtain parameter estimates at corresponding delays.

Consider the first method. To estimate the delay at which the transformation starts we use that delay at which the slope starts rising. For the spatial probe, we assume that the slope cannot be negative; it follows that the transformation starts close to $t = -50$ msec, since the slope versus delay function is steep and, extrapolated to $\beta = 0$, the time value is about -60 msec.

For the spoken identity probe, Sternberg, Knoll, & Leuin (1975) found the slope to be relatively invariant over a large range of probe delays $t \leq 0$, but by $t = 150$ the slope has started to rise. (Figure 6, in Sternberg, Knoll, & Leuin, 1975.) Other data (Figure 12 in that report) indicate that if the slope versus delay function is relatively smooth, it probably starts rising early in the (0,150) interval; we take $t = 20$ msec as a reasonable value. According to the first method, it then follows that the delay in the identity-probe experiment that corresponds to delay t msec in the spatial probe experiment is $t + 80$ msec. Results are shown in Figure 14.

For the second method, we let the additive constant be zero, with the results shown in Figure 15.

According to both analyses, the spatial slope changes relatively more slowly initially and (by necessity) more rapidly later. But the difference is small; further analysis is needed to determine whether the difference can be attributed to sampling error.

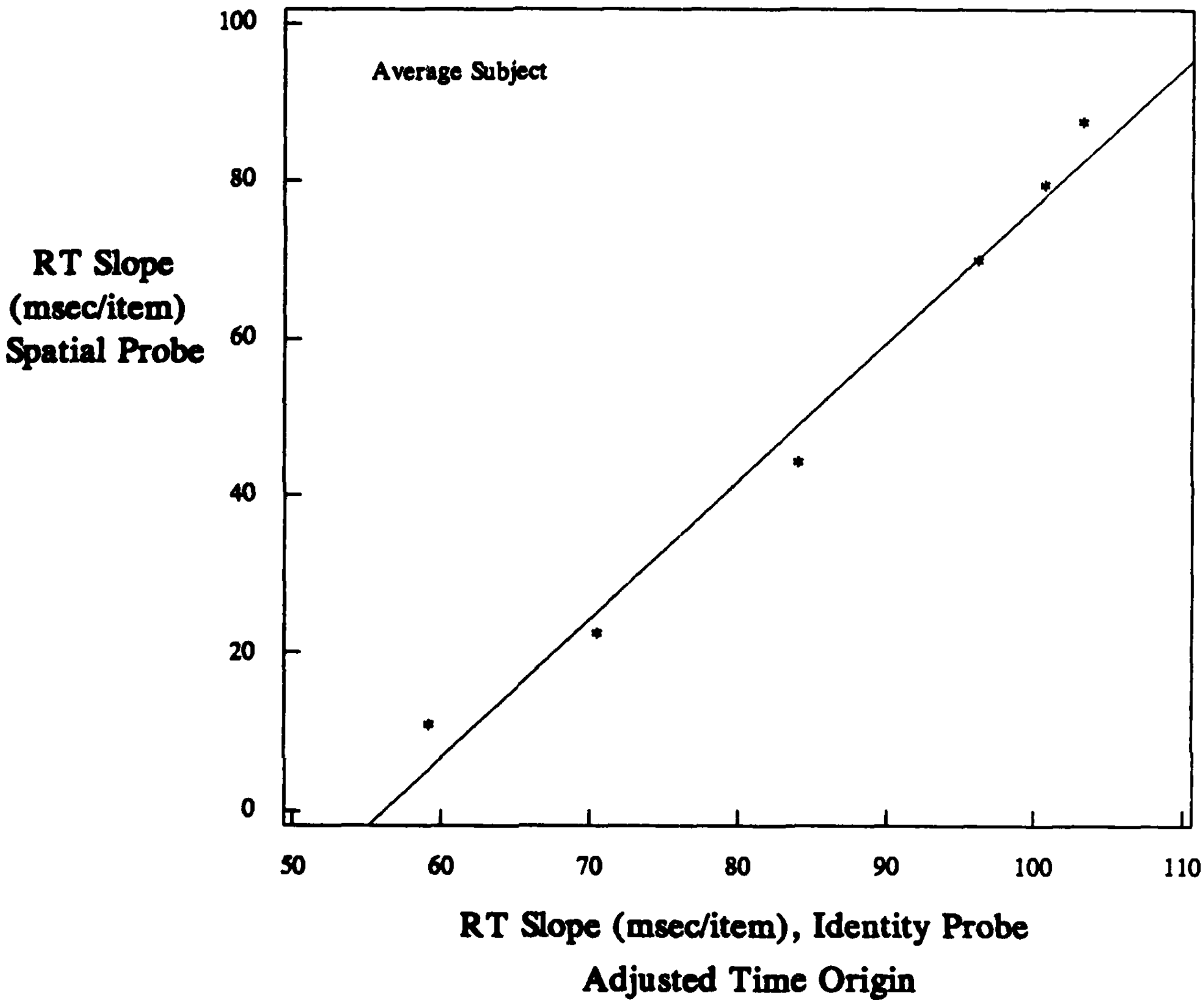

Average Subject
100
80
60
40
20
0
RT Slope
(msec/item)
Spatial Probe
50
60
70
80
90
100
110
RT Slope (msec/item), Identity Probe
Adjusted Time Origin

Figure 14A.

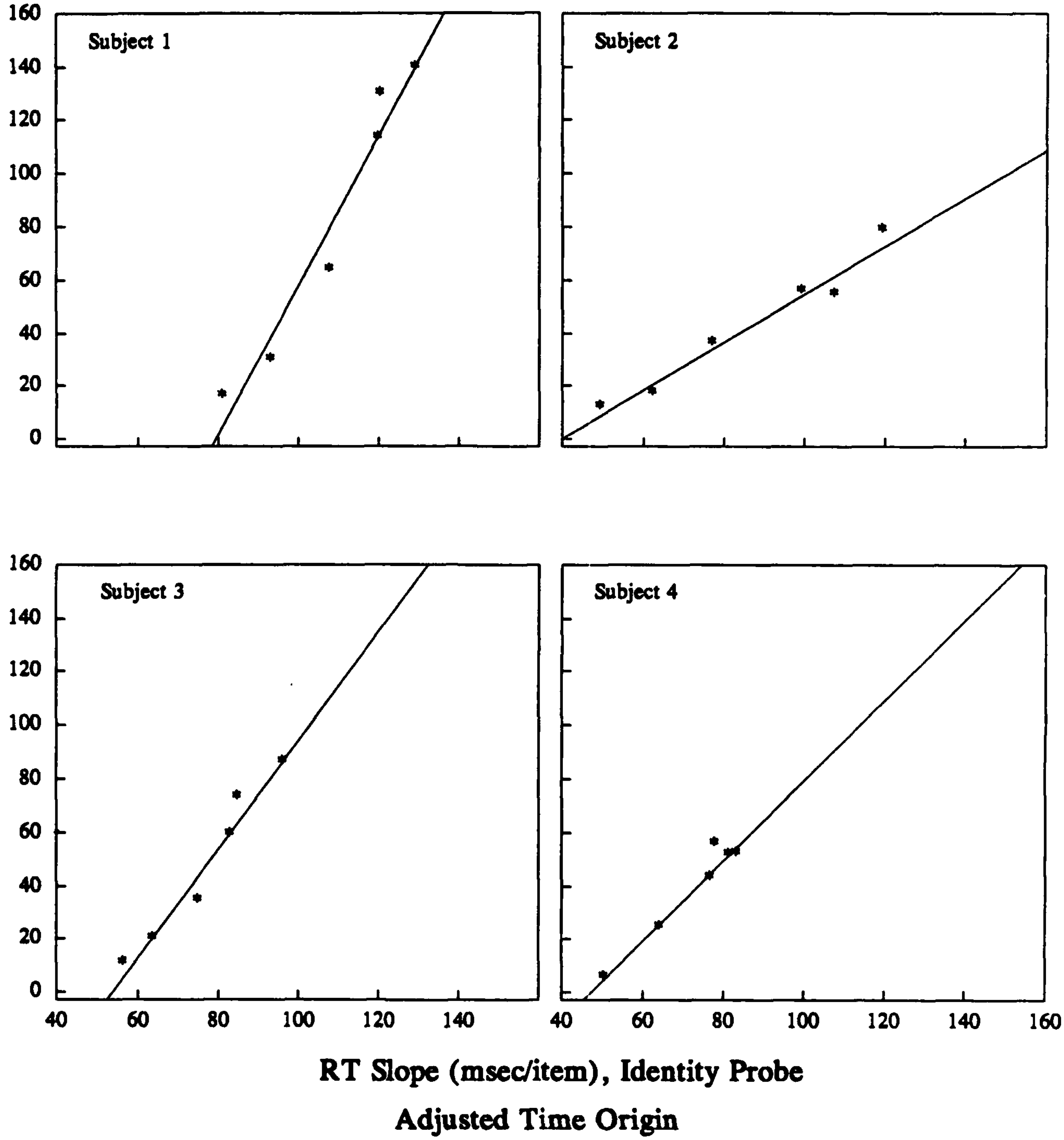

Subject 1
Subject 2
Subject 3
Subject 4
160
140
120
100
80
60
40
20
0
40
60
80
100
120
140
160
RT Slope (msec/item), Identity Probe
Adjusted Time Origin

Figure 14B.

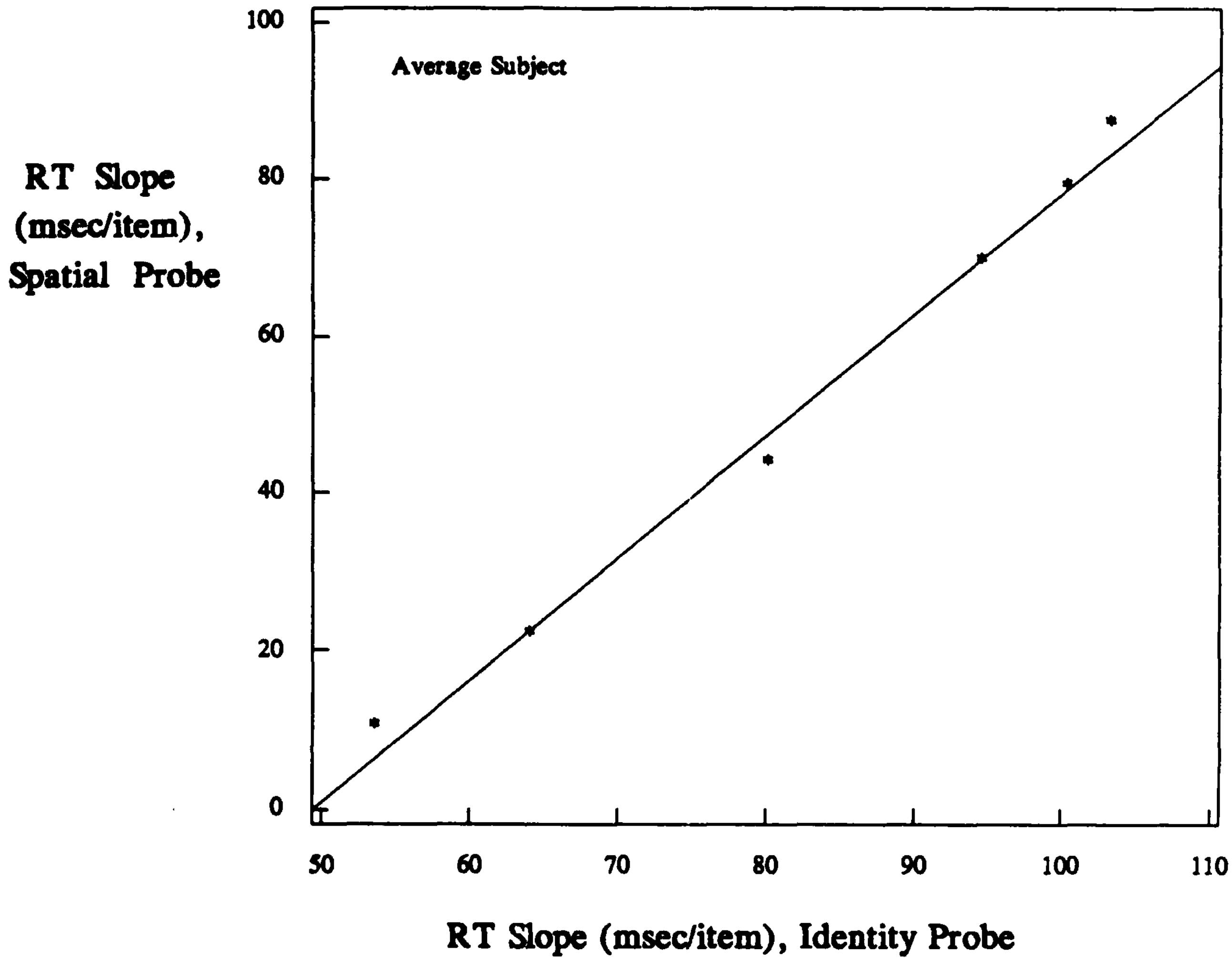

Average Subject
RT Slope
(msec/item),
Spatial Probe
100
80
60
40
20
0
50
60
70
80
90
100
110
RT Slope (msec/item), Identity Probe

Figure 15A.

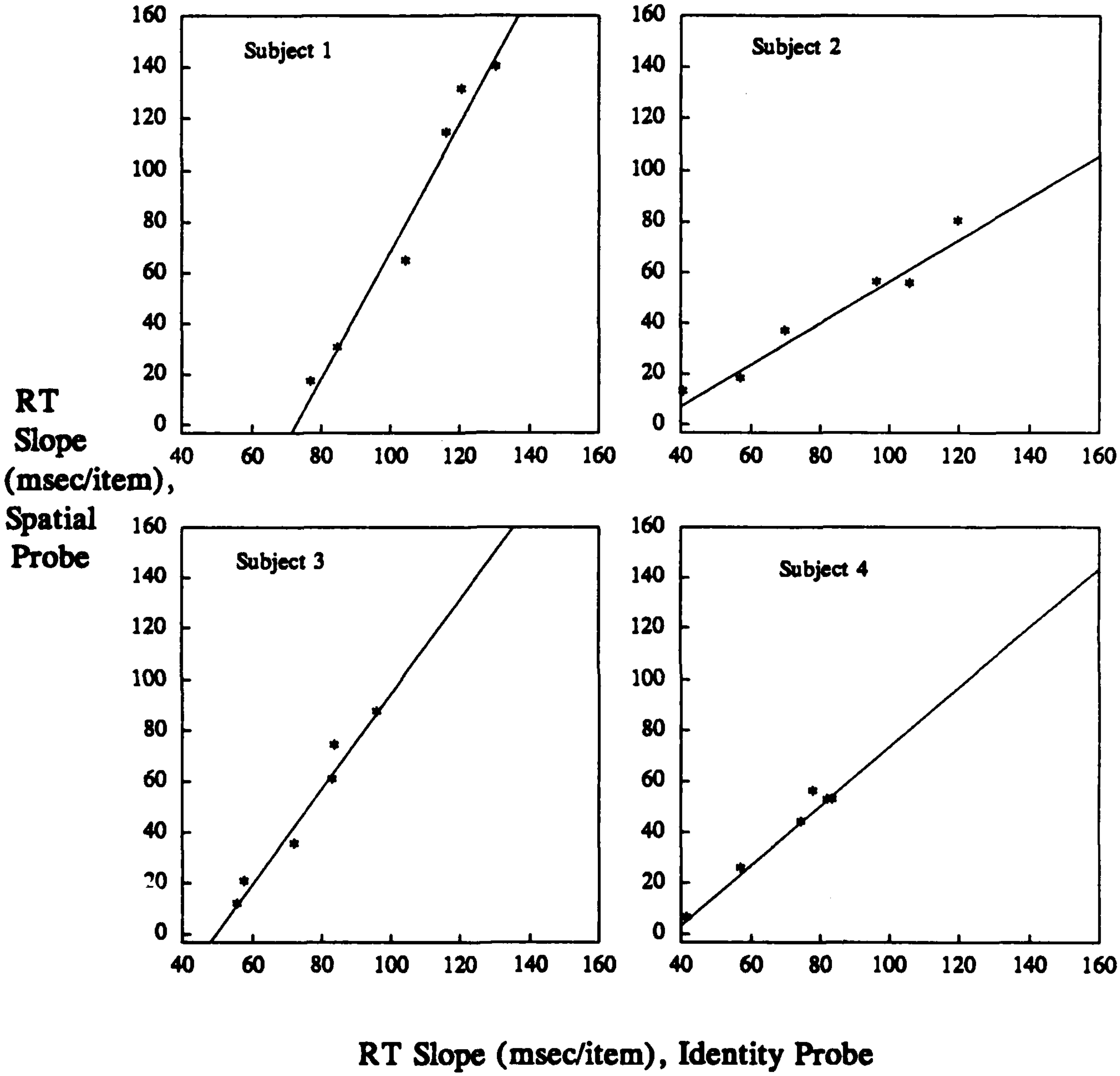

Subject 1
Subject 2
Subject 3
Subject 4
RT Slope (msec/item), Spatial Probe
RT Slope (msec/item), Identity Probe
0
20
40
60
80
100
120
140
160
40
60
80
100
120
140
160

Figure 15B.

17. Nature of the transformation: Test of a probabilistic mixture model

As mentioned in sections above, one of the aspects of our data that is especially intriguing is the persistent linearity of the reaction-time function, regardless of delay. It would seem that for many processes of transformation (e.g., serial, or "limited-capacity" parallel) transformation time would increase with array size. Suppose that the transformation moves the mean RT for an array of a particular size from a point on a flat function to a point on a steep asymptotic linear function. For such transformation processes, the smaller the array, the faster the asymptote is reached. There should then be a range of probe delays for which small and medium-size arrays have reached asymptote with probability close to one, but large arrays have not. For such delays we would therefore expect that the function relating mean RT to array size would be concave down, contrary to the data. We shall see in Section 18 that this conjecture is supported by the behavior of several quantitative models that embody a serial transformation process.

Given a flat function (i.e. no effect of array size) at negative or very brief delays, and a steep linear function (i.e. a linear effect of array size) at the longest delay, with these two retrieval-time patterns representing two different states of the internal representation of the array, one transformation process that would produce a smoothly-changing always-linear function would be one that produced a gradual change in the mixing probability of these two states in a binary (two-component) probability mixture, with the probability associated with the steep-function state being independent of array size, and rising from zero to unity as the delay increases. Such a model might be called a *parallel synchronous transformation process:* at any time, the retrieval process is applied to elements all of which are either in their initial state or in a transformed state, with probability of the latter increasing with probe delay. Such a process could underlie Model 2 of Section 14. Another transformation process that would give rise to a probabilistic mixture of the hypothesized kind is a *parallel independent transformation process:* elements are transformed independently as time passes. This process produces a probabilistic mixture of the initial and final states with a mixing probability that is independent of array size only if the search set, when search is required, contains all elements in the array; the search cannot be limited to the transformed elements alone, as it is in Model 3 of Section 14, for example.

As mentioned in Section 15, a binary probabilistic mixture with changing mixing probability could also account for the finding of strong time-course identity of the slope and intercept of the RT function.

Given such a parsimonious explanation of persistent linearity, it seemed important to test it and, indeed, it was partly for this reason that we analyzed the RT variance, as described in Section 11. (It is the overall variance that is appropriate for testing such a mixture model.) The theory underlying the test is described in Appendix 1.

One intuition about binary (two-component) mixtures that is often expressed, when both of the components are unimodal, is that the mixture distribution should be bimodal. Even if a test of bimodality were easy, this intuition would not be very useful, because it is often false. For example, even when the forms of the component distributions are known (to be normal, e.g.), the mixture distribution will be unimodal if the separation of the component means is sufficiently small relative to the variances. (See, e.g., Everitt & Hand, 1981, Section 2.2.) However, as shown in Appendix 1, any separation of the means will induce a variance increment in the mixture (relative to the weighted average variance of the components), even if it is insufficient to induce bimodality, and, furthermore, the size of the increment is independent of the forms of the component distributions.

In Appendix 1 we describe two methods of testing for this variance increment. The *Means Method* is restricted to array sizes for which the mean RT changes substantially enough over a range of delays so that based on relations among the means, we can associate a mixing probability with each of a set of probe delays with adequate precision; the estimated mixing probability associated with a delay is given by the proportion of the change in mean over the full range that has been achieved by that delay. In the present experiment this was possible for array sizes 3 and 6.

Because the variance increment is at a maximum when the mixing probability is 0.5, we compared predicted and obtained variances at that probe delay for which the estimated mixing probability was closest to 0.5, for each subject and array size. We sought to perform eight tests (array sizes 3 and 6 for each of four subjects). In one case we could not perform the test because mean RT versus probe delay was nonmonotone in such a way that the delay for which the estimated mixing probability was closest to 0.5 was also one of the endpoints of the probe-delay range. For six of the remaining seven tests, the observed variance was smaller than predicted, providing at least weak evidence against the binary-mixture hypothesis.[17] It remains to be seen whether elaborations of any of the models that give rise to a binary mixture will be able to explain this violation, while retaining at least approximately the identity of time course functions for slope and intercept, and the linearity of

17. For subjects 1, 2, 3, and 4, respectively, values of the ratio of observed to predicted variance based, in each case, on data from array sizes 3 and 6, respectively, are (0.279, 0.349), (1.308, 0.657), (0.643, 0.483), and (No test, 0.565). For the seven values, the mean $\pm SE$ is 0.612 ± 0.128, which is shown by a t-test to be significantly less than unity.

the RT function at intermediate delays.

18. Nature of the transformation: Tests of serial-transformation models

In the section above we suggested that a process of serial transformation should produce functions relating mean RT to array size that are concave downward over some range of intermediate probe delays, rather than being linear. In this section we report our efforts to develop and test six models of a serial-transformation process, partly to evaluate this conjecture and assess the extent of any such nonlinearity. Some of the models provide remarkably good fits to the data; our intuition about nonlinearity is borne out, however.

We assume a *serial* transformation process: elements are transformed one at a time. Thus, in contrast to the models considered in Sections 14 and 17, here the probability that an element is in its initial directly-accessible state not only depends on (and declines with) probe delay t, but also depends on (and increases with) array size s. We assume that the rate at which elements are transformed is independent of array size. For a given probe delay some elements may be directly accessible by spatial position, while others may have been transformed and must therefore have their location attributes tested serially to determine which is the target element. In each of a series of epochs a single element is transformed. An array of n elements is completely transformed in the course of a series of n such epochs. The epoch may be either a fixed constant or a random variable in different specific models. For example, consider arrays of two sizes and a delay sufficiently brief such that some elements may have been transformed, but the probability that all elements have been transformed is zero even for the smaller array. Then the mean *number* of elements transformed is the same for both array sizes, so that the mean *proportion* transformed (and thus the probability that search will be required) is larger for the smaller array.

18.1 Six specific models

We have investigated the implications of three different assumptions about the transformation time per element: (1) It has a *gamma* distribution with shape parameter $n = 6$; (2) It has an *exponential* distribution (a less plausible assumption despite its popularity, but useful as a distribution of contrasting shape); and (3) It is a fixed *constant* (least plausible). Because we have assumed no variability in other components of the reaction time, such as encoding of the probe or searching of transformed elements, this third assumption produces a fully deterministic model. (The assumption that these other RT components are fixed constants is, of course, highly implausible; however, we believe that it has no effect on the derivation of predictions, so long as we limit the predictions to mean RT, and so long as we assume, as we have done, that the transformation process ceases when the probe is presented.) For each distributional assumption, we considered two variations in the search process when search is required, thus generating our six models: (1) *Search all (sa):* when search is required the search set includes representations of the full array; and (2) *Search transformed only (st):* When search is required, only those elements that have been transformed at the time the probe is presented are searched.

18.2 Model equations at extreme probe delays

Given a probe delay sufficiently brief such that no elements have been transformed, we assume that all responses are based on a direct-access process with duration D; the sum of all additional components of the RT is denoted A, so that we have

$$T(s,\ t_{small}) = A + D. \qquad (18.17)$$

Given a probe delay sufficiently long such that all elements have been transformed, we assume that a search process is necessary through a search set that contains $s-1$ elements, and we have, for a self-terminating search,

$$T(s,\ t_{large}) = A + \beta_m + (s - 2)(\beta_{mm} / 2). \qquad (18.18)$$

(For an exhaustive-search variant, replace $\beta_{mm} / 2$ by β_{mm}; this variation affects only the interpretation of parameters.) Note that we have assumed that $A(t) = A$ is independent of t: Any dependence of the intercept on probe delay is due entirely to the effect of delay on the matching time, β_m. [18]

18.3 Calculation of the proportion of direct access trials.

If the times for initial processing of the array and the probe were equal, then the time available for the the serial transformation process would equal the physical probe delay: the interval between array onset and probe onset. To avoid making this equality assumption, we included as a free parameter the time interval (positive or negative) between onset of the display and initiation of the transformation process.

We determined the mean number of transformed elements as follows: We drew successive samples from the distribution of transformation times and accumulated their sum. Sampling continued until either all the elements in the

18. Given the large change in intercept with delay, and the fact that the mismatch time must be non-negative, one implication is that the matching time at brief delays is substantial -- of the order of 200 msec.

array were transformed or the next sample would increase the sum beyond the total time available for the transformation process. The proportion of elements that have not been transformed is an estimate of the proportion of direct access trials for this array size and probe delay. For each such array size and probe delay we estimated $p(t)$ by calculating the mean of 100 such sample proportions.

18.4 Fitting procedure for group data

We developed estimates of several of the parameters by using the equations above together with data from extreme probe delays. Thus, we used the mean RT at small t to estimate $A + D$; at large t we used the mean RT at $s = 2$ to provide an estimate of $A + \beta_m$ and the slope of the function relating mean RT to array size to provide an estimate of $(beta_{mm} / 2)$. Two additional parameters are needed to fully specify the model: (1) the mean transformation time per element, and (2) the time at which the transformation process begins. As mentioned above, we permitted the time origin of the transformation process to be a free parameter. If extraction of location information from the probe took longer than the initial processing of the array, some elements might be transformed when this information became available even when the probe was presented simultaneously with the array. Conversely, if initial processing of the array was relatively slow, all digits could be in their initial, direct-access representation even for a slightly delayed probe.

The three distributions and two search processes give six models. The data we used were drawn from the average over subjects of the slopes and intercepts for seven delays, ($t = -.05$, 0, .15, .35, .65, .95, and 1.65 sec). For reasons discussed earlier, we ignored the intercept value for the shortest (negative) delay. We informally adjusted the five parameters of each model to give the best fit to the resulting 13 data points. The slope and intercept data and the predictions for the six models are shown in Figure 16. The constant-st model clearly provides the worst fit; the constant-sa model provides a much better fit, but systematically underestimates the slope. Of the four stochastic models, the gamma-st model is somewhat worse than the others. The remaining three models were investigated further as described below.

18.5 Fitting procedure for data from individual subjects

For each of the three remaining models (exponential-sa, exponential-st, and gamma-sa) we performed a search in the five-dimensional parameter space to determine the best fit to each subject's data. For each choice of parameters we calculated the root mean square deviation (*RMSD*) between the mean RT and the predicted value. Because of the arbitrariness of the time origin for the -50 msec probe delay, we excluded data from that condition, leaving six probe delays.[19] Given the six delays and four array sizes, the resulting *RMSD* is

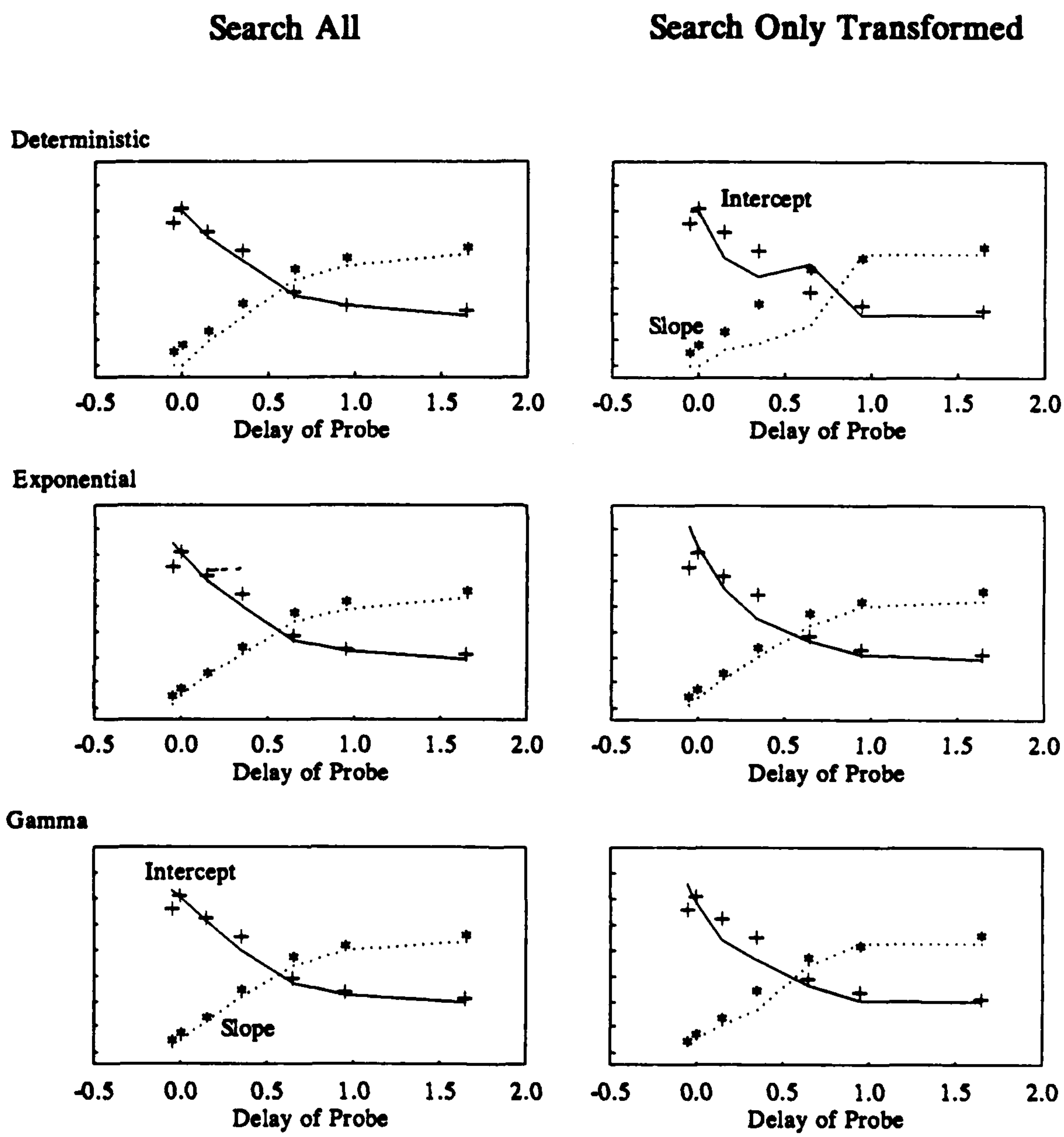

Search All
Search Only Transformed
Deterministic
Intercept
Slope
-0.5 0.0 0.5 1.0 1.5 2.0
Delay of Probe
Exponential
Gamma

Figure 16.

calculated over 24 comparisons. Table 1 summarizes the results for individual subjects. Goodness of fit for all three models is substantially worse for Subject 1 than for the others; Indeed, the differences among subjects are larger than the differences among models. The data for three of the four subjects are fitted best by the exponential-sa model (the leftmost column in the table); Figure 17 permits comparison of the mean slopes and intercepts (averaged over subjects) with the corresponding mean fitted values.

18.6 Systematic curvature of the predicted RT function at intermediate probe delays.

Figure 18 shows the mean RTs (squares) and the corresponding mean fitted values of the exponential-sa model (curves). The downward concavity we had expected of serial models is thus revealed in the predicted functions. To test the consistency of this curvature difference between model and data we fitted a quadratic function to the observed mean RTs for each subject and probe delay, and to the corresponding fitted values for each model. The predicted values show more downward concavity than the data (as evidenced by a more negative quadratic coefficient). Across probe delays the fitted values for the exponential-sa model have a smaller quadratic coefficient than the observed data in 6 of 7 instances for each of the four subjects. Similar comparisons for the exponential-st model give counts of 6, 5, 6, and 7 for subject 1, 2, 3, and 4, respectively; for the gamma-sa model the counts are 6, 6, 6, and 7. Overall, 73 of 78 comparisons show the model values to be concave downward relative to the data; Table 2 presents the mean quadratic coefficients.

The serial transformation, serial search models account for much of the variance in our data with only five parameters. We have shown that the fit is not very sensitive to the shape of the distribution of transformation time per element, so long as it is not a fixed constant, nor to whether the search set contains transformed elements only, or all elements. The serial transformation, however, leads to an array-size function that is concave downward, in conflict with our observations.[20]

---

19. A better solution would be to determine a separate parameter that represented the intercept difference between probes that precede the array and others.

20. The delicacy of this comparison, and the observation of a tendency for the observed functions to be concave upward rather than linear suggests that we should not regard this as conclusive evidence against serial models of the transformation process.

		Model			
		Exponential Search All	Exponential Search Transformed Only	Gamma Search All	Average
Subject	1	33.2	34.8	33.9	34.0
	2	12.9	14.7	13.7	13.8
	3	13.1	17.0	14.6	14.9
	4	13.8	11.9	13.0	12.9
Average		19.6	18.3	18.8	18.9

Table 1
Root mean squared deviation (msec) for three versions of the serial transformation, serial search model.

	Data	Model		
		Exponential Search All	Exponential Search Transformed Only	Gamma Search All
Subject 1	9.08	-4.08	-4.94	-3.80
Subject 2	0.21	-4.06	-4.41	-4.67
Subject 3	-1.23	-5.21	-4.89	-4.69
Subject 4	3.20	-1.56	-3.50	-2.29
Average	2.82	-3.73	-4.43	-3.86

Table 2
Quadratic coefficient averaged over probe delay for mean reaction times and predicted values of three versions of the serial transformation, serial search model.

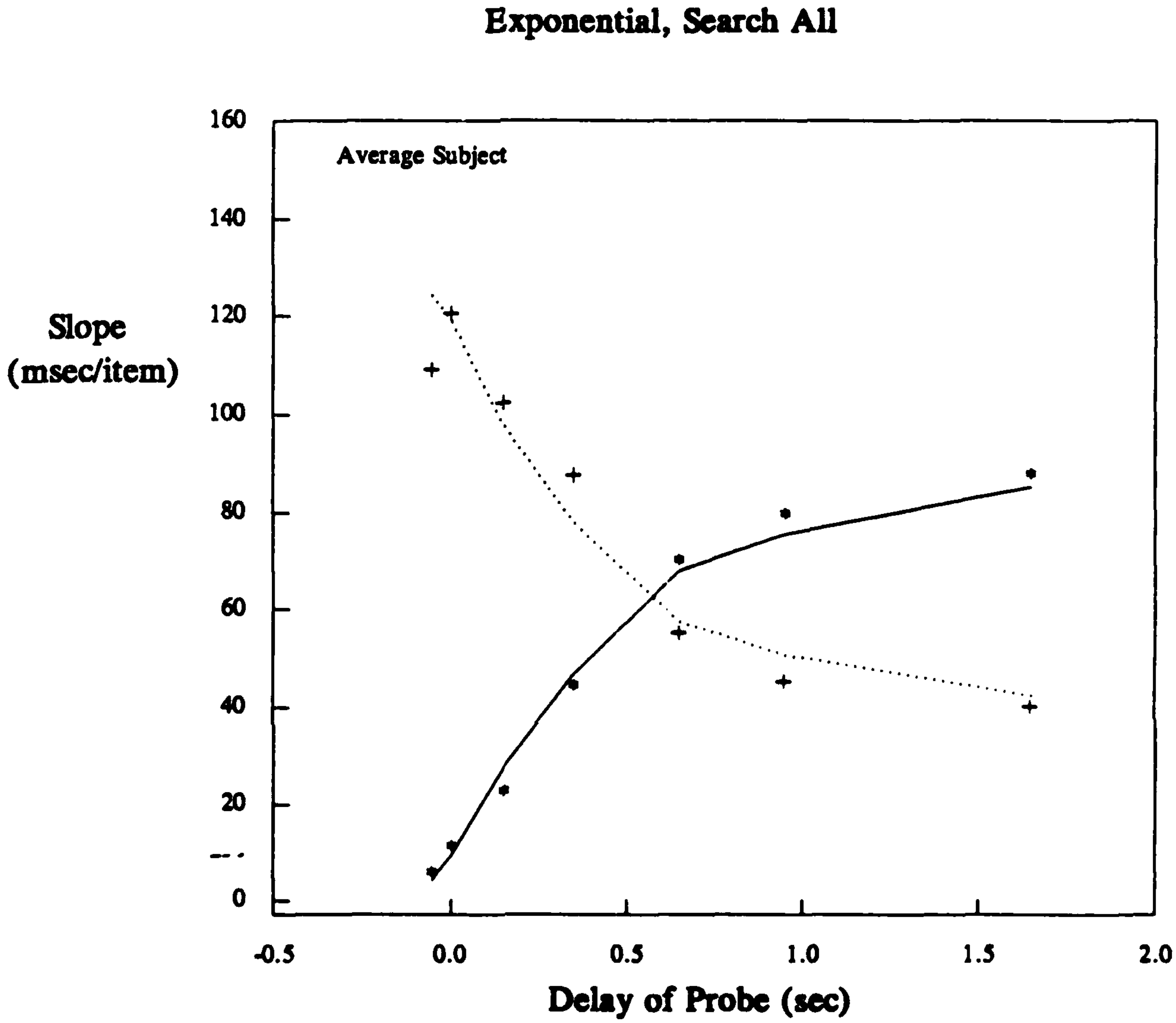

Exponential, Search All
Average Subject
Slope
(msec/item)
160
140
120
100
80
60
40
20
0
-0.5
0.0
0.5
1.0
1.5
2.0
Delay of Probe (sec)

Figure 17A.

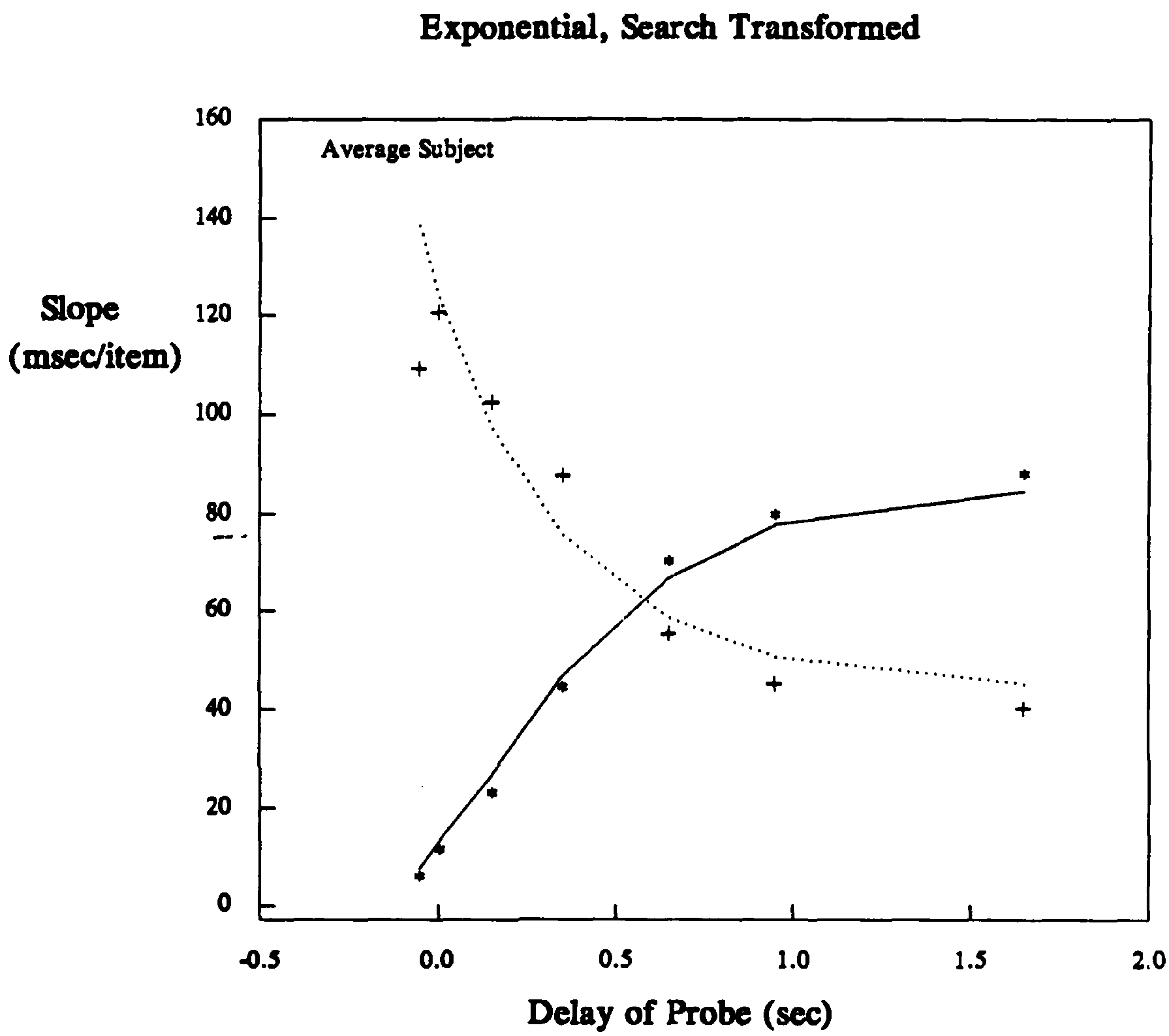

Exponential, Search Transformed
Average Subject
Slope (msec/item)
160
140
120
100
80
60
40
20
0
-0.5
0.0
0.5
1.0
1.5
2.0
Delay of Probe (sec)

Figure 17B.

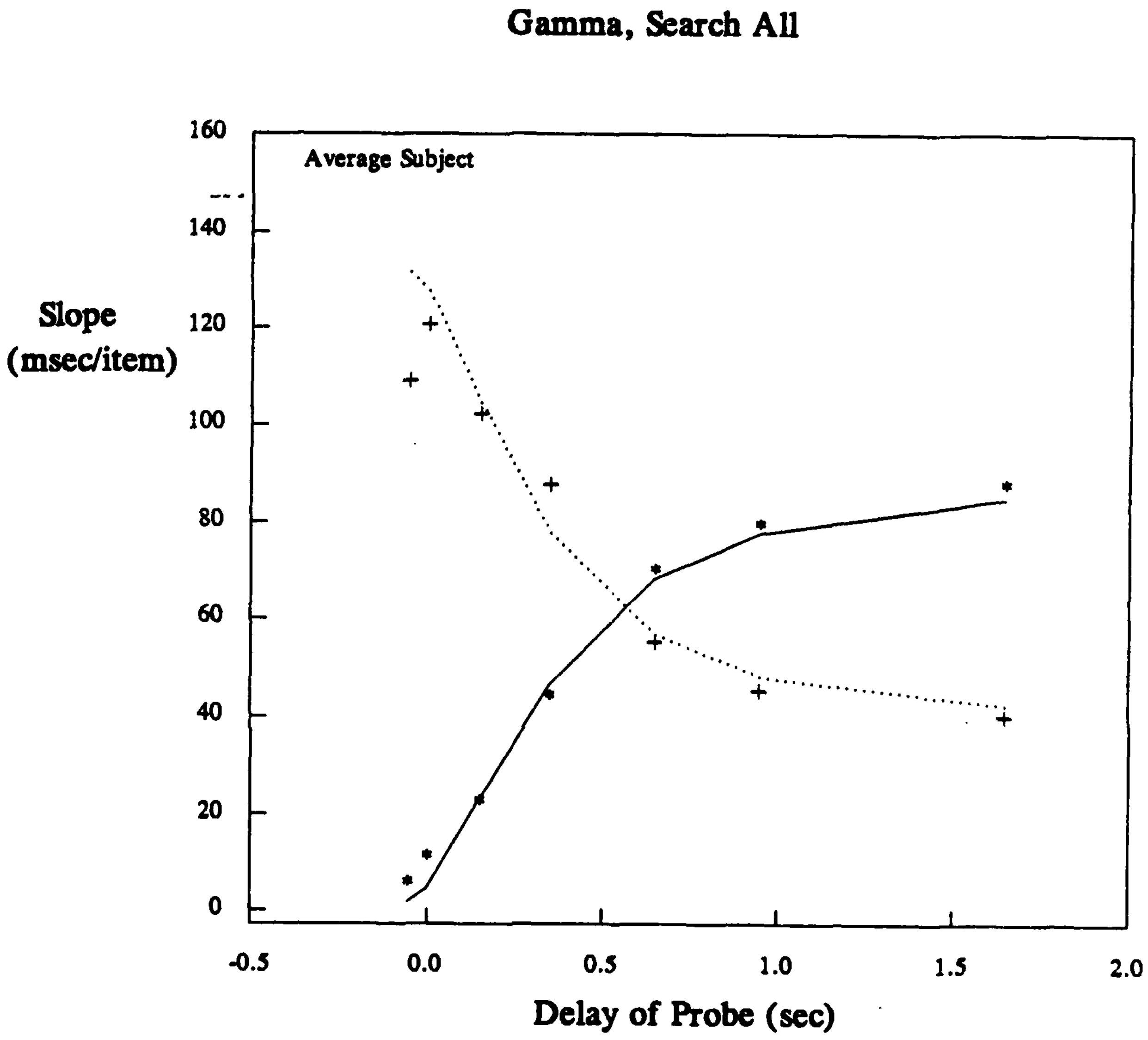
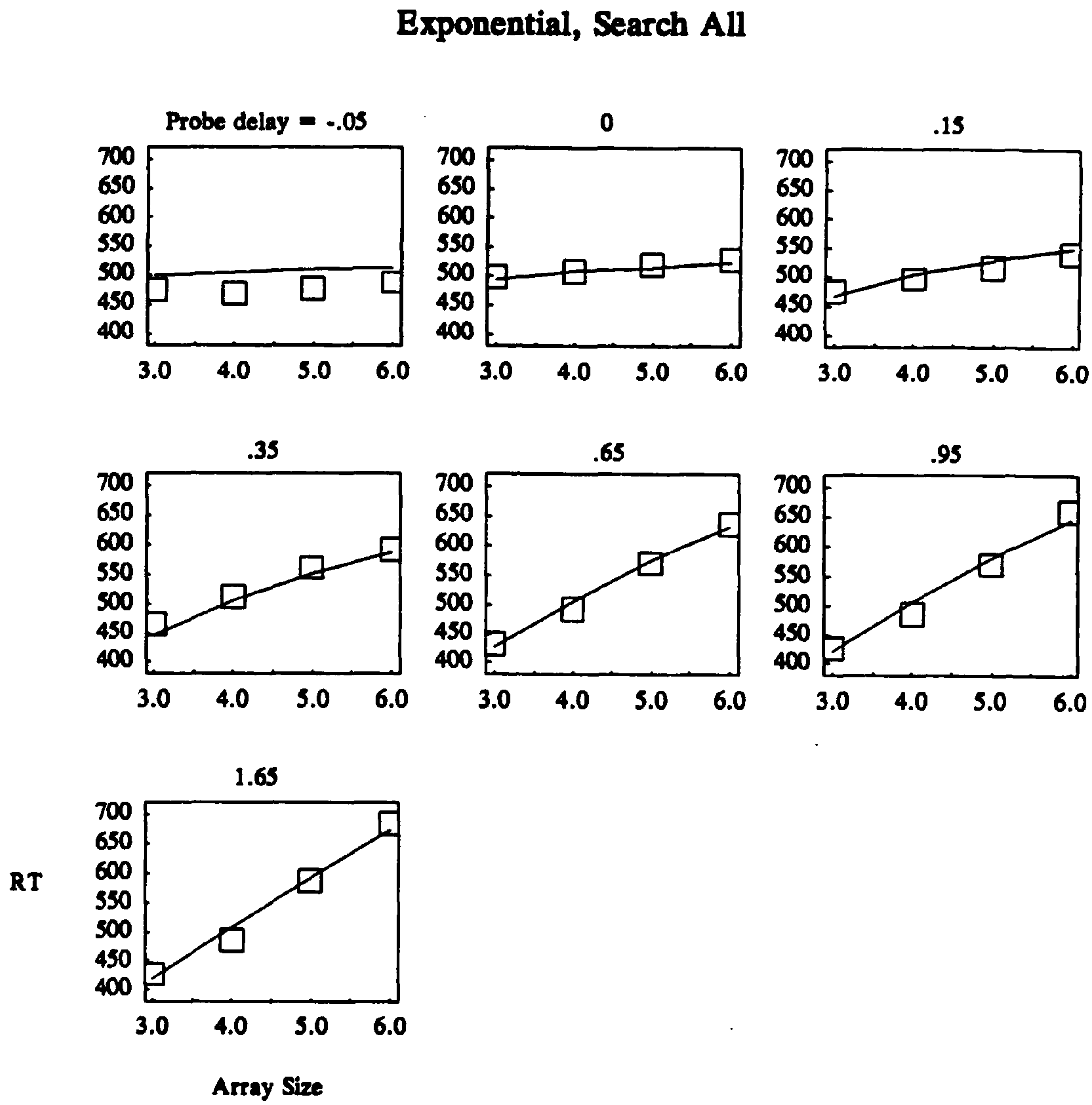

Gamma, Search All
Average Subject
Slope (msec/item)
160
140
120
100
80
60
40
20
0
-0.5
0.0
0.5
1.0
1.5
2.0
Delay of Probe (sec)

Figure 17C.



Exponential, Search All
Probe delay = -.05
0
.15
.35
.65
.95
1.65
700
650
600
550
500
450
400
3.0
4.0
5.0
6.0
RT
Array Size

Figure 18.

19. Alternative explanations of the approximate invariance of reaction time with array size for leading and simultaneous probes

19.1 Direct access by spatial position

We were led to the present set of experiments partly to test our hypothesis that a visual or spatial representation is characterized by the property of direct access by spatial position: that is, no search over other elements is needed to retrieve information about a particular element when that element is specified by its spatial position. Our finding of approximate invariance of reaction time with array size early in the life of the memory of the display would then be consistent with the initial display representation being visual. At least two other explanations of the approximate invariance of reaction time with array size for leading and simultaneous probes present themselves as candidates, however.

19.2 Marker-target integration

According to this hypothesis, when the displays of visual marker and array are in sufficiently close temporal proximity, an internal representation is formed of their superimposed images. The marked numeral then has the marker lines integrated with it, making it a highly distinctive pattern, easily found by a search process. Search for such a distinctive pattern among unadorned numerals is very rapid, so the effect of display size is negligible. In effect, the set of elements searched - i.e., the set of distinctive patterns made up of digit plus marker - is always of size one, regardless of the number of elements in the display. Thus we find no array-size effect, not because search is unnecessary, but because the set of elements searched is always of size one.[21]

19.3 Marker-induced shift of visual attention

According to this hypothesis, the abrupt onset of the visual marker automatically causes visual attention to shift rapidly to its location, rather than merely informing the subject of that location. Yantis and Jonides (1984) suggested that abrupt visual onsets might have this property. The shift of attention presumably takes place more rapidly than a shift of eye position. If an array item is displayed at that locus during the period that attention is concentrated there, then that is the first item examined (and tested for its location) in any search. If we assume that the search for a location-item pair

21. This possibility was suggested by Julian Hochberg in a personal communication.

under these conditions is self-terminating, then the search ends where it began, so the size of the array has no effect. Thus we find no array-size effect, not because search is unnecessary, but because the *order* of the (self-terminating) search places the target element first.

In a subsequent report we shall describe an experiment in which we compared performance when the marker is visual with performance when the marker is a tactile stimulus together with a tactile-visual mapping rule, to test the above alternatives, which depend on the marker being visual. As reported briefly in Sternberg, Knoll, & Turock (1985), the tactile marker, when appropriately timed, also produces reaction times that are approximately invariant with array size, which argues against the second and third alternatives above.

20. Alternative interpretations of the increased effect of array size with delay

20.1 Loss of the direct-access property

The possibility that interests us the most is that one of the characteristics that distinguishes the initial visual representation is the direct-access property introduced in Section 3.3. As the memory ages the initial representation is transformed into one that does not have this property.

20.2 Change from retinotopic to spatiotopic coordinates

It has been proposed that the internal representation of visual information changes over time from being referred to retinal spatial coordinates, to being referred to extra-retinal coordinates. At the time of its presentation and for a brief period thereafter, the marker display is presumably referred to retinal coordinates. It follows that if the marker is presented in close temporal proximity to the array, then they are both referred to the same coordinates. It would seem reasonable to suppose that when this condition is met, less "computation" is required to determine spatial relations between constituents of the two displays: Their locations can presumably be "directly" compared. On this hypothesis, when the two displays are separated in time, they would be referred to different sets of coordinates. The direct-access property might depend on the use of the same coordinate system for array and probe, rather than being an inherent property of the array representation alone.

The similarity of our findings for tactile and visual markers (mentioned in the preceding section, and to be described in detail in a forthcoming report) argues strongly against a change from a retinotopic representation as an explanation of the rapid elimination with delay of the direct-access property, because the mapping from tactile marker to visual array would have to be "indirect" at all delays.

20.3 Differential reduction of spatial uncertainty

The marker can appear in any one of six display locations. From the subject's viewpoint, when the marker is early, all six locations are possible. As the array is processed, however, the subject comes to learn where the array is located in the display space - i.e. which are the filled locations. For a six-item array there is no reduction in spatial uncertainty relative to an early marker, but for smaller arrays the acquired information serves to reduce spatial uncertainty. That is, for a delayed marker, the subject has learned from seeing the array what the set of possible marker locations might be. This information could guide the subject in where to center her attention in visual space, and in how widely to disperse it. If the discrimination of marker location is faster when attention is less widely dispersed, or when attention is at the marker's location with higher probability, then the discrimination of the location of a delayed marker will be faster with smaller arrays. We might therefore observe an increasing array-size effect even while the direct-access property persisted, because of an indirect effect of array size on the time to discriminate the marker.

In a forthcoming report we shall describe an experiment in which we explicitly manipulated spatial uncertainty to measure its effect with a probe delay that normally produces results consistent with direct access. Results from that experiment suggest that as the probe is delayed, any differential reduction in spatial uncertainty that favors small arrays has a negligible effect on reaction time.

20.4 Differential reduction of response uncertainty

For an early probe the subject has no information before the probe that limits the response to a set of alternatives smaller than the full set of ten digits. That is, from the subject's viewpoint, the response can be any one of the ten digits with equal likelihood. As the subject processes the array while awaiting a delayed probe, however, she assimilates information about which digits it contains, thereby reducing response uncertainty, and she also has an opportunity to "prime" the processing operations related to these digits. The smaller the array, the greater the reduction in response uncertainty, and the greater the likelihood of having primed operations that are needed in order to generate the required response. These effects may reduce the time that is taken by organizing and executing the response. RT would therefore increase with array size, not because of an increased time to retrieve the internal representation of the required item, but because of the time taken by organizing the response.

It is worth noting that the RT for the naming of *displayed* numerals is little affected by the size of the set of alternatives. (See, e.g., Experiment 5 in Sternberg, 1969.) Under the conditions being considered here, however, the numeral is not displayed at the time the response is required.

In a forthcoming report we shall describe an experiment in which we explicitly manipulated response uncertainty to measure its effect with a probe delay that normally produces results consistent with direct access. Results from that experiment suggest that as the probe is delayed, any differential reduction in response uncertainty that favors small arrays has a negligible effect on reaction time.

20.5 Differential increase of memory load

Suppose that as the subject awaits a delayed marker, she identifies the array elements and stores them in working memory. The resulting memory load is greater for larger arrays. RT might then be slowed by an amount that increases with the size of this memory load (and hence the size of the array), merely because the maintenance of the load shares a limited capacity with the processes that generate the naming response. Thus, after the information is stored, RT will be longer for larger arrays, even though the direct-access property persists with delay, and there is no search over the other items in the array.

This alternative depends on the existence of two effects: First, a memory load must be generated, and second, such a load must slow the naming response to a marker by an amount that increases with its size. In a forthcoming report we shall describe several experiments designed to search for such effects. One previously reported result suggests that if there is any such effect it is relatively small. In one experiment with the probed-reciting procedure (Section 4) we mixed trials that required the naming of either the leftmost or rightmost element of an array with trials that required reciting of all the elements, either left-to-right or right-to-left. Because reciting of the full array is required on some trials, this procedure seems more likely than the spatial-probe procedure to generate a memory load. Yet although we found an effect of array size on naming a single element in response a a delayed probe, it was relatively small. (See Sternberg & Knoll, 1985, Experiment 3.)

21. The role of naming in controlling the transformation process: Location-specific matching

In the *location-specific matching procedure*, the probe is a character, presented above the location of one of the displayed items; the subject says "yes" if the probe matches the item below it, and "no" otherwise. Unlike the two paradigms discussed in Section 4 and the spatial-probe procedure, this one does not require a naming response. (One desirable consequence is that it can be generalized to displays of shapes that are unfamiliar and that do not have well-learned names, in contrast to alphanumeric characters.) Preliminary data with digit displays indicate that when probe and display are approximately simultaneous, array size has a negligible effect on mean RT, consistent with the property of direct access by spatial location (Turock, 1985). When the probe is delayed, mean RT increases linearly with array size, with increasing slope, indicating another simple search process, and gradual loss of the direct access property. These results indicate that the transformation process revealed by the other paradigms does not depend on the requirement - shared by those paradigms - to name one or more of the array elements, and also provides evidence that response uncertainty (Section 20.4) does not play an important role in the effects we observe.

The inclusion of a matching item (a mislocated target) in an unprobed location on occasional trials in the location-specific matching procedure also permits testing *selective processing* at different probe delays. (If selectivity fails, and items in unprobed locations are compared to the probe, we expect interference when the array contains a mislocated target.) For early probes, but not for later ones, preliminary data support selective processing.

22. Implications of the transitoriness of direct access for traditional partial-report experiments

Let use assume that a transformation of visual memory with properties similar to the one discussed in the present report also takes place in experiments such as those of Averbach & Coriell (1961), in which the array is very large relative to those we used, and in which there is no explicit time pressure. Then the existence of an array-size effect that changes with delay suggest a possible error in the estimated duration of visual memory inferred from such experiments.

The aim of Averbach & Coriell's experiments was to measure the identifiability of a target element selected randomly by the experimenter, as a function of the age of the memory of the array in which it was embedded. They recognized that processes of discriminating (*d*) the location of the marker, and finding (*f*) the internal representation of the target element were required after the marker appeared and before interpretation of the internal representation could begin. Indeed, they estimated the "readout time," $t = t_d + t_f$ taken by these two processes, and added this estimate to the physical probe delay, τ, giving $\tau + t = \tau + t_d + t_f$ as the corrected age of the array memory at which element identifiability for a probe with physical delay τ was being measured. They assumed, however, that t was independent of τ, consistent with their (implicit) assumption that the property of direct access by spatial position obtains over the full range of their probe delays.

In contrast, our findings suggest that the two components of t must be separately considered, and that whereas the first may be independent of τ, the second is not. The first, t_d, is the amount that must be added to τ to give the effective probe delay discussed in Footnote 14 (the age of the memory when marker position is discriminated).[22] The second, t_f, is the duration of the process of finding the internal representation of the element associated with that position. Our results suggest that t_f depends strongly on τ. Even for arrays of size $2 \leq s \leq 6$, which are small relative to theirs, we find that t_f increases from a value close to zero to a value that may be as large as the slope of the steepest reaction-time function multiplied by the largest array size, or about 480 msec.

23. Implications of the changing effect of array size with probe delay for explaining 'the cost of visual filtering'

We believe that our spatial-probe procedure can be regarded as a *filtering* task, as defined by Kahneman & Treisman (1984, p. 31). In terms of our experiments their definition can be rephrased as follows: (1) The display contains relevant and irrelevant stimuli -- i.e., target and nontarget elements. (2) The target element controls a relatively complex process of response selection and execution -- i.e., identifying and naming the numeral. (3) Property P_1 (being centered between two line segments), which distinguishes the target element from nontargets, is different from property P_2 (the target element's shape), which determines the appropriate response.

In a series of experiments reported by Kahneman, Treisman, & Burkell (1983), subjects were asked to name a word, color, or shape as fast as

22. In Section 10 we argue that it is likely that the effective probe delay is greater than the physical delay: The sum of the time to transmit information about the marker from the retina to the relevant place(s) in the visual system plus the time to discriminate its location is greater than the time to transmit information about the array from the retina to relevant place(s) in the visual system. If so, then the delay of -50 msec may effectively be greater than zero.

possible, either when displayed alone, or in the context of one or more irrelevant objects. The addition of an irrelevant element increased the time to produce the name by varying amounts, depending on details of the conditions: this "cost of visual filtering" ranged from about 10 msec to 40 msec, in unpracticed subjects. The cost was essentially eliminated by advance information about where the target would be located within the display. The authors conclude that the effect results from "attentional competition": "irrelevant objects and events disrupt the deployment of attention when choice responses, such as reading or naming, are required." (p. 520)

It seems possible to us that the cost of visual filtering is the same as the array-size effect that we have been investigating, and that its magnitude is therefore quite sensitive to the age of the internal representation of the display at the time the location that defines the target is discriminated. Indeed, differences in the time taken by such discrimination may partly account for the large range found for their effect by Kahneman, Treisman, & Burkell.

To make our viewpoint clear, let us consider one of their procedures, where the target was a word to be named, composed of white letters, and the irrelevant elements that could be present in varying number were strings of red symbols other than letters. Either color (white *versus* red) or category (letters *versus* other symbols) could be used to discriminate the location of the target element. Suppose that P_1 in this case was color. Both color (P_1) and shape (P_2) information are represented in memory. While P_1 is being discriminated, which is required to determine the location that defines the target, the memory representation of P_2 is aging. On our analysis the obtained filtering cost depends on how much such aging has occurred at the time P_1 is discriminated. In the Kahneman, Treisman, & Burkell paradigm, unlike ours, the time at which P_1 is discriminated cannot be manipulated by varying the time at which P_1 is presented. (One test of our analysis would be to vary the discriminability, and hence the discrimination time, of P_1 by, e.g., varying the similarity of target and nontarget colors: The cost of filtering should increase with increasing similarity.) Insofar as our analysis is correct, it may be misleading to explain the effect as a result of competition among displayed elements for visual attention, unless one believes that an increase in the amount of such competition (rather than a change from one representation to another) explains the increasing array-size effect with probe delay.

24. Summary

This memorandum is a continuation of the series of reports on our research on the short-term dynamics of human visual memory. Others in the series include Sternberg, Knoll, & Leuin (1975), Sternberg & Knoll (1985), Sternberg, Knoll, & Turock (1985), Turock (1985), and Sternberg, Turock, & Knoll (1986).

In this report we outlined our approach to the problem, embodied in four experimental procedures, and reported in detail on findings from a set of experiments using one of them: the spatial-probe procedure with a visual probe. The principal phenomenon is our finding that the effect of array size (3-6 digit elements) on the time to name a visually marked element in a brief visual display increases rapidly with marker delay, revealing a rapid and dramatic transformation of the internal representation of the array. For early markers the effect of array size is negligible, indicating a property of direct access by spatial position, and spatially-selective attention. Direct access is one of several properties we discuss that may distinguish visual from nonvisual representations. For late markers the effect of array size on mean reaction time is a linear increase.

In Sections 1-2 we reviewed the history of the problem, and described the essential features of our approach. In Sections 3-4 we discussed some properties of representations that are visual that may be diagnostic, and related them to findings from two other procedures we have used: In terms of these properties the rapid transformation appears to change the representation from being visual to nonvisual. In Sections 5-8 we considered some general issues of experimental design and analysis in assessing an array-size effect, and indicated how we have attempted to address them in our application of the spatial-probe procedure.

In Sections 9-11 we reported the effects of array size and probe delay on the mean and variability of the reaction time, and on the error rate. In all three measures an increase with array size emerges only when the probe is delayed. Because the function relating mean RT to array size is linear at all delays, we can characterize it by slope and intercept parameters. In Sections 12-13 we discussed the behavior of these parameters as the probe is delayed, and in Section 14 we discussed the choice of intercept in relation to three models of transformation and search of the array memory (Section 14).

In Sections 15-16 we provided evidence for the conclusion that the time courses of the change with probe delay of slope and intercept parameters are identical, and we argued that such time-course identity supports a particular view of the underlying transformation process, in which the transformation expresses itself as a binary probability mixture with a changing mixing probability. One basis of such a mixture would be a process in which array elements were transformed in parallel. But implications that we developed in Appendix 1 of such a mixture hypothesis for the reaction-time variance were violated by our data (Section 17). As an alternative we reported in Section 18 on the testing of a set of models that embody a serial transformation process. Several of these models fit the data remarkably well, but we again noted a systematic discrepancy.

Finally, in Sections 19-20 we discussed alternative explanations of the approximate invariance of reaction time with array size for early probes, as well as the increasing effect of array size as the probe is delayed, we mentioned some preliminary evidence about the relevance of the naming response to the transformation process (Section 21), and we considered the implications of our findings for some other effects that have been reported in the literature on visual information processing (Sections 22-23).

25. Appendix 1: Use of the variance to test a binary mixture hypothesis

In this appendix we derive the relationships that permit us to perform the test of the binary-mixture hypothesis described in Section 17as well as some more general tests of that hypothesis.

25.1 Variance of a binary mixture

Let $T = T_a$ with probability ρ and $T = T_b$ with probability $1-\rho$, where T_a (T_b) has mean μ_a (μ_b) and variance σ_a^2 (σ_b^2). Then

$$M \equiv E(T) = \rho\mu_a + (1-\rho)\mu_b \,, \tag{25.1}$$

and

$$E(T^2) = \rho\sigma_a^2 + (1-\rho)\sigma_b^2 + \rho\mu_a^2 + (1-\rho)\mu_b^2 \,. \tag{25.2}$$

From these expressions, together with

$$Var(T) = E(T^2) - E(T)^2 \tag{25.3}$$

we find that

$$V \equiv Var(T) = \rho\sigma_a^2 + (1-\rho)\sigma_b^2 + \rho(1-\rho)(\mu_a-\mu_b)^2. \tag{25.4}$$

Note that the sum of the first two terms changes linearly with ρ (the mixing probability), starting at σ_a^2 (when $\rho = 1$) and ending at σ_b^2 (when $\rho = 0$), just as does the mean, which starts at μ_a (when $\rho = 1$), and ends at μ_b (when $\rho = 0$). On the other hand, if $\mu_a \neq \mu_b$ then the third term is zero at the extreme values of ρ, and reaches a maximum where $\rho = 0.50$. Thus, if $| \mu_a - \mu_b |$ is large relative to $| \sigma_a^2 - \sigma_b^2 |$, the variance may change nonmonotonically with ρ; in any case it is clear that a plot of V as a function of M, with ρ as the parameter, will be concave downward, with the deviation from linearity reflecting the third term in Eq. 25.4. Our intuitions about mechanisms other than mixtures reflect the widespread view that the variance grows with the mean, which leads us to expect the function for such mechanisms to be more linear.

25.2 Relations among variances of binary mixtures with three mixing probabilities

One difficulty in applying the above result to experiments such as ours is that it requires us to be able to identify and collect data under conditions where $\rho = 1$ (so that μ_a and σ_a^2 can be estimated) and where $\rho = 0$ (so that μ_b and σ_b^2 can be estimated). In the present section we generalize the results above, eliminating this requirement.

First, to enhance understanding and develop a result we shall be using later, we prove the following theorem.

Theorem 1 (Compound Mixing) Let T_i, $i = 1, 2, \ldots, n$ be a set of binary (two-component) mixtures of pure components T_a and T_b, such that $T_i = T_a$ with probability ρ_i, and $T_i = T_b$ with probability $1-\rho_i$. Two members T_i and T_j of the set are distinct if $\rho_i \neq \rho_j$. Then any member T_i of the set can also be written as a binary mixture of any pair of distinct members. That is, letting T_1 and T_n be the distinct pair (without loss of generality), there exists a mixing probability π_i such that $T_i = T_1$ with probability π_i and $T_i = T_n$ with probability $1 - \pi_i$. Furthermore,

$$\pi_i = \frac{\rho_i - \rho_n}{\rho_1 - \rho_n}. \qquad (25.5)$$

Theorem 1 means that given the hypothesis that RTs at any probe delay are distributed as a binary mixture of pure components, they are also distributed as a binary mixture of "impure" components - i.e. as a mixture of other mixtures of the same pure components. The mixture hypothesis can thus be tested by asking with regard to the distribution at any delay whether it is a mixture of distributions at any two other delays.

Now we consider the mean and variance of such a mixture in relation to the mean and variance of its (impure) components. Suppose three different mixtures of T_a and T_b, with mixing probabilities, means, and variances,

$$\rho_1, \rho_2, \rho_3; \ M_1, M_2, M_3; \text{ and } V_1, V_2, V_3,$$

respectively.

Theorem 2 (Mean and Variance Relations among Mixtures) Let

$$\pi = \frac{\rho_2 - \rho_3}{\rho_1 - \rho_3} \qquad (25.6)$$

with $\rho_1 \neq \rho_3$.

Then

$$M_2 = \pi M_1 + (1 - \pi)M_3, \tag{25.7}$$

and

$$V_2 = \pi V_1 + (1 - \pi)V_3 + \pi(1 - \pi)(M_1 - M_3)^2. \tag{25.8}$$

These generalizations of Eqs. 25.1 and 25.4 can be proved as follows: To prove Eq. 25.7, replace the M_i by their equivalents from Eq. 25.1, replace π by its definition in Eq. 25.6, and simplify. To prove Eq. 25.8, express the V_i in terms of parameters of the pure components as in Eq. 25.4, express π in terms of the ρ_i from Eq. 25.6, and simplify.

Theorem 2 means that given that the distributions from a set of conditions differ only in being binary mixtures of the same components with different mixing probabilities, then any three conditions have the property that the variance of the third is specified by the variances of the other two and the means of all three.

Eqs. 25.7 and 25.8 may be combined to provide a symmetric expression of the relation of variances and means. We replace π in Eq. 25.8 by its value from Eq. 25.7,

$$\pi = \frac{M_2 - M_3}{M_1 - M_3}, \tag{25.9}$$

and rearrange, to get

$$(M_3 - M_1)V_2 + (M_2 - M_3)V_1 + (M_1 - M_2)V_3$$
$$= (M_3 - M_1)(M_2 - M_3)(M_1 - M_2). \tag{25.10}$$

25.3 Testing strategy

The strategy we adopted is based on our intuition that for nonmixture mechanisms the deviation from linearity of the function relating variance to mean would be smaller than for a mixture mechanism. If so, the most sensitive test would tend to be one where $\pi(1 - \pi)$ is maximized, or where the mixing probability π is close to 0.5. After choosing two endpoints on the probe-delay continuum, we therefore determined that probe delay for which $\hat{\pi}$ was closest to 0.5, and compared the observed and predicted variances at that delay.

We used two different methods to associate a π-value with a particular probe delay. In the *Means Method* we estimated π separately for each array size, replacing the expectations in Eq. 25.9 by sample means and using that equation as an estimator. Our second method, the *Slopes Method,* depends on the assumption that the time course is independent of array size; we used the slope of the RT function in place of the means of Eq. 25.7 to provide the estimates.

Both methods depend critically on having a good estimate of the mixing probability associated with a particular probe delay. Clearly this requires that the mean or slope (depending on method) changes rapidly within the range of probe delays being considered. For the Means Method, for example, this requirement is met only by data for array sizes 3 and 6; the mean RTs for array sizes 4 and 5 change relatively little with probe delay.

Another consideration is the choice of endpoints of the range of probe delays. On the one hand we want a wide range of delays, to maximize the difference between means at the two endpoints so as to maximize the final term in Eq. 25.8. On the other hand there may be difficulties of interpretation associated with certain early delays (which may, for example, influence the mean RT, and hence the Means Method, but not the slopes, and hence not the Slopes Method.) For example, whereas for most of the delays we studied, RT was measured from the onset of the 50 msec marker, this was not so for the -50 msec delay condition, in which RT was measured from the onset of the array. This choice could, of course, be altered, by simply incrementing all RTs by 50 msec; the important point is that for purposes of the Means Method, we may not know, a priori, how to make RT measurements that are comparable up to better than an additive constant at all delays.

We also felt there was a chance that even delay zero might not be comparable to longer probe delays, because initial processing of probe and array might not be accomplished as efficiently simultaneously as when they were asynchronous. One possibility is that such a failure of "unlimited-capacity" parallel processing might increase the mean RT, but not necessarily influence the slope of the RT function; this would again suggest avoiding delay zero for the means method. In consequence we used 150 msec as our shortest delay with that method.

25.4 Alternative: Fitting the overall variance function

If the mixture hypothesis can be rejected by using data limited to just three delays, then there would seem to be little advantage in pursuing the hypothesis further. But should the hypothesis be more tenable, more detailed evidence bearing on it could be found by fitting the mixture model to the entire variance function - i.e., the function for a particular array size that relates variance to probe delay for all delays within the range of interest.

One approach to doing this would be to use the means, M_i, for a series of probe delays $i=1, 2, .., n$, to estimate the corresponding π_i:

$$\hat{\pi}_i = \frac{\hat{M}_i - \hat{M}_n}{\hat{M}_1 - \hat{M}_n} \qquad (25.11)$$

and then to fit parameters ν_1 , ν_n that correspond to the extreme variances V_1 , V_n . The sum of squared deviations to be minimized is then

$$\sum_i [V_i - \pi_i\nu_1 - (1 - \pi_i)\nu_n - \pi_i(1 - \pi_1)(M_1 - M_n)^2]^2 \qquad (25.12)$$

25.5 Alternatives to the variance for detecting mixture distributions

Because of its sensitivity to extreme observations, the variance may not be the best statistic for testing a mixture hypothesis. Furthermore the variance may not reflect the distinguishing characteristics of a mixture as sensitively as would other statistics. For example, if the lower tails of the two components are separated, then the lower tail of the mixture should be similar to the lower of the two lower tails; similarly the upper tail of a mixture should be similar to the uppermost tail of two separated upper tails. Furthermore this property should be observable for any mixing probability, so long as it is not too close to either one or zero, so results should depend less heavily than the variance test on the adequacy of the method used to estimate the mixing probability.

A general approach that permits tests based on tail properties, as well as tests based on measures of spread more robust than the variance (and perhaps measures of other potentially sensitive properties, such as kurtosis) is to compare an empirical mixture of observed distributions to an observed distribution hypothesized to be a mixture of these components, with a specified (estimated) mixing probability. Thus, suppose we have distributions T_1 , T_n at two selected endpoints on the probe-delay continuum, and have an estimate of the mixing probability π_i for a distribution T_i at a selected intermediate probe delay. Then if the mixture hypothesis is valid we should find that a mixture with weights π_i and $1 - \pi_1$ of distributions T_1 and T_n should match T_i in every respect.[23]

23. Another method of testing for binary mixtures that we have not yet applied to our data has been developed by Thomas (1969).

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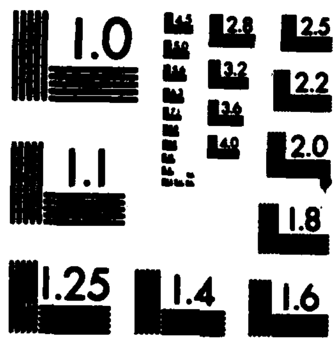

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