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On the nature of the span of apprehension

Peter Dixon[1] **and Judith M. Shedden**[2]

[1] Department of Psychology, University of Alberta, Edmonton, Alberta T6G 2E9, Canada
[2] University of Pittsburgh, USA

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Summary. Typically, people can only report about four or five items from a briefly presented array of alphanumeric items. A new span task was used to explore the basis of this limitation. In Experiment 1, performance suffered when very brief display durations were combined with a verbal-load task, but no significant effects of display duration were found when there was no verbal load. In Experiment 2, a similar interaction was observed between verbal load and the presence of a visual suffix; performance was worse in the verbal-load condition with a visual suffix, but no such effect was observed without verbal load. In both experiments, poorer performance was associated with enhanced serial-position effects. The results can be explained on the assumption that the verbal-load task required some processing resources, and that the quality of information in visual working memory depends on available resources. Thus, both brief-array presentation and the visual suffix degrade the information in visual working memory, but span performance is impaired only when processing resources are relatively scarce.

Introduction

In 1885, Cattell inferred that the number of unrelated letters that could be processed simultaneously was limited to about four or five. Sperling (1960) replicated this basic result, and found that when a large number of alphanumeric items were presented tachistoscopically, only about four or five items could be reported accurately. A variety of explanations have been proposed for this performance limitation, including limitations on what can be perceived in a single glance, limitations on the size of short-term memory, limitations in the speed with which information can be transferred from one store to another, response-output interference, perceptual interactions among items in the display, and refractory periods in an information-transfer mechanism. All of these proposals may contain some element of truth, but all have some shortcomings as well. We use the term *span of apprehension* to refer to this limitation in performance, but without any commitment to the nature of this limitation. In the present article, we present a new way of examining the span of apprehension, and present some data that bear on the explanations of this performance limitation. We conclude that the span of apprehension is determined jointly by the quality of perceptual information and the resources required to maintain information in visual working memory.

Models of the span of apprehension fall into two general classes: processing-limitation models and storage-capacity models. Processing-limitation models assume that performance is limited by the speed or accuracy of some process required for performing the task. Storage-capacity models account for the span of apprehension by assuming that performance depends on a storage buffer with a fixed capacity, and that when the number of items presented exceeds the capacity of the buffer, performance is impaired. Below, we review some of the storage and processing models that have been proposed for the span of apprehension. This review suggests that neither type of model can account for all of the important results in the literature, and that an adequate account must include aspects of both.

Processing-limitation models

Cattell's (1885) interpretation of the span of apprehension was in essence a processing-limitation model. He hypothesized that briefly presented items must be perceived and recognized before they can be named, and that this apperception process could operate on a number of different items simultaneously. However, the effectiveness of simultaneous apperception diminished with the number of pre-

Correspondence to: P. Dixon

sented items, and little evidence for simultaneous apperception was obtained with more than four or five letters. From our point of view, the explanation postulated by this type of model can be roughly characterized as a limitation on the capacity of the apperception process.

A related proposal is that there are limitations on the perceptual processes that identify and encode features from the visual display, and that these limitations constrain the number of items that can be reported from a brief display. Evidence for this position comes from the research of Wolford (e.g., 1975) on serial-position effects in the span of apprehension. When accuracy of report is plotted as a function of serial position in the array, performance resembles a W, with higher accuracy in the center of the array and at the ends. This pattern can be explained by the combination of two factors. First, items are assumed to be more difficult to perceive the farther they are away from the fovea. Presumably, this decline in performance is due to relatively peripheral factors, such as the decline in photoreceptor density with increasing retinal eccentricity. Second, it is assumed that the presence of contours near an item interferes with the perception or identification of that item. This effect may be referred to as lateral interference, and probably occurs during the process of combining feature information so as to identify the item (cf. Estes, 1982). Thus, the serial-position effect would seem to be caused by limitations of perceptual and identification processes, rather than by processes that retain or manipulate item identities.

Further evidence regarding the nature of serial-position effects comes from studies of visual masking. When an array of letters is followed by a masking stimulus of visual noise, report performance generally declines. However, this decline in performance tends to be specific to items near the center of the array; end items are relatively unaffected (Merikle, Coltheart, & Lowe, 1971; Merikle & Coltheart, 1972). This interaction between a perceptual variable (visual masking) and serial position suggests that serial-position effects in general may be determined by the quality of perceptual information used in item identification. In particular, it seems likely that the visual mask interferes with the process of localizing items in space (Mewhort & Campbell, 1978) and that poorer localization adversely affects the availability of items for later report (cf. Mewhort, 1974). Because end items are more easily localized, they would be less affected by the visual noise mask.

Wolford (1975) argued that these kinds of perceptual limitation apply not only to performance at particular serial positions, but also to aggregate performance on the array as a whole. For example, when the entire array is displaced to the left or to the right so that items become more peripheral on average, the number of items reported declines systematically as a function of the amount of displacement. The peak in span performance of about four items occurs only when items are centered upon the point of fixation (Wolford & Hollingsworth, 1974b). A straightforward interpretation of this result is that the serial-position effects observed in the task are part and parcel of the span limitation. That is, the limitation on items reported overall occurs because items at certain positions are difficult to identify. From these considerations, it would seem that the span of apprehension reflects primarily limitations on the available perceptual information.

However, the data from Sperling's (1960) partial-report experiments argue against such an interpretation. In Sperling's task, subjects reported only a subset of the items in the visual display; a partial-report cue following the display indicated the items to be reported. Sperling found that when the cue came immediately after the offset of the display, subjects could report a much greater proportion of the display than without the cue. His findings suggest that most of the array was perceived and was still available for report shortly after display offset. It follows that the limitation apparent when subjects report all of the items could not have been due to perceptual processes. In a sense, the results of the partial-report task indicate that the original span of apprehension procedure was flawed, confounding the process of perceiving the items with the process of reporting them. The fact that most items potentially could be reported under partial-report instructions thus suggests that the limitation in performance must occur later in processing, after some initial perceptual stage.

The *transfer-speed* account of the span of apprehension is based on this conclusion (e.g., Sperling, 1960). In this view, the available perceptual information resides in one buffer and must be recoded and transferred to a second buffer before it can be reported; it is this transfer process that is assumed to limit the number of items that can be reported in the span task. We refer to the first buffer as *visual persistence* to capture the fact that the buffer contains visual information about the display that persists for some period of time after its physical offset. However, our use of this term should not be taken to imply that visual persistence is a unitary phenomenon with a fixed set of properties. Indeed, a variety of research indicates that partial-report performance can be supported by at least two different kinds of representation, both of which are subsumed here under the term visual persistence (Di Lollo & Dixon, 1988; Dixon & Di Lollo, 1991; Turvey, 1978; cf. Coltheart, 1980). The logic of the transfer-speed model is that the perceptual information in visual persistence lasts only a limited period of time, and that only some of the items can be transferred to the more enduring second buffer before they are lost. For example, if visual persistence lasts 300 ms and the transfer process works at a rate of 100 ms per item, then only 3 items would be recovered before information from the display was lost.

An important prediction of a simple transfer-speed model is that there should be large and robust effects of display duration. If the visual persistence of a display simply adds to the total amount of time that items are available (e.g., Loftus, Johnson, & Shimamura, 1985), then longer stimulus displays should provide more time to transfer items to durable storage. Assume, for example, that the transfer process operates at 100 ms per item and a brief display is followed by 300 ms of persistence. Then with a display duration of 100 ms, items should be available for 400 ms, and 4 items should be reported. On the other hand, if the display were presented for 500 ms, then the items should be available for 800 ms and 8 items should be reported, an increase of 100%. However, no such dramatic effects have been found in a wide range of experiments manipulating stimulus duration in span tasks. Occasionally, small positive effects are obtained (Irwin & Yeomans, 1986; van der Heijden, 1981), but more often there are no effects of stimulus duration (e.g., Sperling, 1960; Di Lollo, 1978), and under some circumstances, negative effects of stimulus duration are found (Di Lollo & Dixon, 1988; Dixon & Di Lollo, 1991). Coltheart (1980) also notes that the transfer-speed model fails to account for effects of display luminance and post-exposure masking. Thus, no simple account of the span of apprehension can be found in either perceptual-processing limitations or in speed-of-transfer limitations. Below we consider a number of storage-capacity models of the span of apprehension.

Storage-capacity models

The general nature of storage-capacity models is that performance asymptotes near 4 items because some storage buffer has been filled, although particular models differ in terms of the hypothesized nature of this buffer. It is sometimes suggested that the performance limitation involves the capacity of short-term memory (e.g., Estes & Taylor, 1964; Sperling, 1960). However, there are a number of reasons to doubt this interpretation. To begin with, most estimates of the capacity of verbal short-term memory are significantly larger than the 4- or 5-item limitation that is typically observed in span-of-apprehension tasks. For example, Drewnowski (1980) estimated memory span for letters to be 6.29 items, and Crannell and Parrish (1957) estimated letter span to be between 6.0 and 6.2 (see van der Heijden (1981) for a different view of this issue).

A second argument against the short-term memory-limitation model was made by Wolford and Hollingsworth (1974a). Generally, investigations of verbal short-term memory have found that when information is lost from short-term memory, acoustic confusions predominate over other types of error (e.g., Conrad, 1964; Sperling & Speelman, 1970; Wickelgren, 1965). Wolford and Hollingsworth found that errors in span-of-apprehension tasks tend to be visual errors rather than acoustic errors. That is, when a subject fails to report an item correctly, he or she is much more likely to report a visually similar item than an acoustically similar item. In sum, verbal short-term memory is unlikely to be the source of the span of apprehension because both the number and nature of the errors people make are inconsistent with what is known about short-term memory.

Another type of storage account was proposed by Sperling (1967). He noted that the maintenance of items in verbal short-term memory was mediated by covert rehearsal of the items. On the basis of this observation, he hypothesized that part of the process of transferring items to short-term memory would consist of loading an articulatory motor-command buffer. The contents of this buffer would then be used to generate the covert articulation necessary to maintain the items in verbal short-term memory (cf. Baddeley, 1986). Sperling hypothesized that the capacity of the motor-command buffer was significantly smaller than the capacity of verbal short-term memory, and that this smaller limitation was the main source of the span-of-apprehension limitation. Although such a model can account for the fact that the span of apprehension is smaller than short-term memory span, it has difficulty with the results reported by Wolford and Hollingsworth (1974a). That is, one might anticipate that errors might occur when the motor buffer is filled to capacity, and that these errors would consist of articulatory confusions, not the visual confusions they found. However, the most serious evidence against the articulatory motor buffer is research done by Scarborough (1972) that suggests that the span of apprehension does not depend on the involvement of articulatory processes at all.

Scarborough (1972) asked subjects to try to retain as many items as possible from a brief visual display while at the same time retaining as many items as possible from a verbal-memory set. After the visual display, a cue indicated whether subjects should report the visual-display items or the verbal-memory items. In Scarborough's data, the report of the visual items was almost as good with a concurrent verbal-memory load as without it, and there was relatively little loss of accuracy in reporting when the delay between the display and the report cue was as long as 2 s. In other words, the span of apprehension was largely unaffected by the maintenance of verbal information in short-term memory. This finding clearly indicates that the span of apprehension cannot be determined in an important way by either the capacity of verbal short-term memory or the process of verbal rehearsal associated with maintaining items in short-term memory. Instead, Scarborough's results suggest that the span of apprehension is determined by some other storage capacity that is essentially visual.

We refer to the storage capacity implicated by Scarborough's results as *visual working memory*. We hypothesize that visual working memory is similar to Baddeley's (1986) concept of working memory in that its contents are determined in part by the resources available for maintaining items. On the other hand, visual working memory is distinguished from verbal working memory in that its contents are assumed to be essentially visual. In the present report, we develop the idea that the span of apprehension is determined primarily by the capacity of this visual working-memory store.

This view has a number of important merits. For example, it readily explains why errors in the span of apprehension are primarily visual rather than auditory or articulatory, and why there is little effect of array duration. However, it is difficult to reconcile this position with the serial-position effects found by Wolford, Merikle, and others. For example, if performance in the span task is determined by visual working-memory capacity, why is accuracy at some serial positions limited by perceptual factors such as retinal eccentricity, lateral interference, and pattern masking? It is difficult to account for such effects as being due to simply a lack of perceptual information at certain positions. For example, the results of partial-report tasks suggest that there is sufficient perceptual information to identify all of the items if the partial-report cue is presented shortly after array offset, even if those items occur at problematic serial positions. In addition, perceptual limitations should not affect the overall capacity of visual working memory, and consequently it is difficult to see why offsetting the array left or right into the periphery should reduce the span of apprehension, as was found by Wolford and Hollingsworth (1974b). In sum, an appeal to the capacity of visual working memory alone is unlikely to provide an adequate account of the span of apprehension; some additional processes would seem to be implicated by the interactions with serial position.

In the present article, we examine the relationship between serial-position effects and the span-of-apprehension limitation. The general plan of this research was to look for interactions between serial position and other variables that might affect the processing and storage of items from the array. In Experiment 1 we manipulated the duration of the array and verbal short-term memory load. Although these two variables have been found to have little effect on overall performance in the span task, serial-position data have rarely been reported, and interactions between serial position and verbal load are likely to tell us something about the locus of the serial-position effects. In Experiment 2, we investigated the involvement of visual working memory more directly by presenting a distracting visual suffix and again examining the interactions with serial position. The results from these experiments suggest a model in which the capacity of visual working memory is not fixed, but rather is determined jointly by the quality of perceptual information and the resources available for maintaining information in memory.

Experiment 1

The traditional span-of-apprehension task has several problems that we wished to avoid in the present research. As Sperling (1960) noted, having subjects report all of the items they see confounds the process of perceiving and retaining the items with the process of reporting them. In addition, it has been suggested that requiring the verbal report of the items interferes with either the retention or the continued processing of the remaining items, producing output interference (e. g., Dick, 1971). Moreover, requiring subjects to make a verbal report may tend to produce results that depend on the contents of verbal short-term memory, even if the items are more easily retained in some visual form. In other words, requiring verbal report may put artificial constraints on overall performance or on the strategies subjects adopt for performing the task.

To address these concerns, we investigated the span of apprehension using what in effect was a partial-report task: we asked subjects to respond on the basis of only one of the items in the display. We cued subjects for report only at very long delays to ensure that little information remained from visual persistence. Townsend (1973) had shown that information about the identities of items in a briefly presented array lasts much longer than information about the locations of those items. Consequently, in the present task we asked subjects to respond simply on the basis of item identity.

In our task, an array of items was presented briefly. Then, after a wait of a second or more, a single target item was presented. The subject's task was to report whether or not the target item had been present in the array. This procedure is essentially the target-array task used by Briand and Klein (1988), Di Lollo and Moscovitch (1983), Dixon (1985, 1986), and Townsend (1973), and is similar to the partial-report task used by Merikle et al. (1971). Most of the researchers using this method have been concerned with the interference that occurs when the target item is presented 100–200 ms after the array, and so collected most of their data at short intervals between array and target. In the present research, we focused on the factors that affect asymptotic performance reached in this task at relatively long intervals. We assume that this asymptote reflects the span of apprehension.

We used this new task to investigate the nature of the serial-position effect in the span of apprehension. Two variables were considered in Experiment 1: the duration of the array and verbal short-term memory load. Although both of these variable have been shown to have minimal effects on overall performance in span tasks, they may have important effects on the serial-position data. For example, if the serial-position effect is determined by the quality of the available perceptual information (as is suggested by the work of Wolford and others), one might expect to find interactions between serial position and array duration. That is, if displays of longer duration lead to superior registration and integration of visual features, serial-position effects would be generally smaller with longer durations. In addition, Scarborough (1972) suggested that the presence of verbal load reduces the involvement of verbal recoding and verbal short-term memory in the span of apprehension. This kind of effect on processing may be evident in the serial-position data even though verbal load has relatively little effect on overall performance.

Method

Observers viewed a brief display of nine letters, and then decided whether a single target letter had been one of the items in the array. The array was presented for a duration ranging from 50 to 200 ms. There were two conditions in the experiment. In the load condition, observers were required to retain in short-term memory two digits for the duration of each trial; the no-load condition did not have this requirement.

Items in the array were capital letters selected randomly without replacement from the set of consonants excluding M and V. The stimuli were displayed black-on-white in the center of a white fixation field 1.4° high by 4.4° long. They were presented on a 30-cm monochrome monitor at a distance of about 70 cm. At that distance, characters subtended about 0.3° of visual angle horizontally and about 0.4° vertically. The experiment was run in a semi-illuminated room with a space-average luminance of about 9 cd/meter^2. The monitor was adjusted so that the characters were displayed at near maximum contrast ($100 \times (L_{max} - L_{min})/(L_{max}+L_{min}) = 95\%$ contrast). The space-average luminance of the white background field on the monitor was about 229 cd/meter^2.

The procedure on each trial in the no-load condition was as follows. When the computer was ready, the rectangular white fixation field was displayed in the center of the monitor. The trial began when the observer pressed both of the response switches in a hand-held response box. After 500 ms the nine items were presented in a row for 50, 100, or 200 ms. After an interstimulus interval of 1,500 ms, a single target item was presented. The target remained on the screen until the observer responded "present" by pressing the right-hand response switch or "absent" by pressing the left-hand response switch. There was a pause of about 1 second between trials. The procedure in the load condition was the same except that each trial began with the simultaneous presentation of

Table 1. A′ and proportion correct in Experiment 1

	A′	Accuracy on present trials	Accuracy on absent trials
Load condition (ms duration)			
50	.666	.677	.529
100	.756	.762	.564
200	.724	.744	.531
No-load condition			
50	.744	.711	.617
100	.698	.672	.568
200	.752	.724	.591

two randomly selected digits for 500 ms, with the array following after an interstimulus interval of 1,000 ms. Observers were required to recall the digits orally at the end of each trial.

The no-load condition was done in one session; the load condition was done in a second subsequent session. Both sessions contained a block of practice trials followed by seven blocks of test trials. In each block there were 54 randomly ordered trials in which each of the three stimulus durations was used an equal number of times. Half of the trials at each duration were present trials (in which the target letter matched one of the letters in the stimulus array), and half were absent trials (in which the target letter was not in the array). On present trials, the target item occurred at each serial position in the array exactly three times. At the end of each block, observers received feedback about their overall accuracy in that block. Each session lasted about 50 min.

The observers were nine undergraduates at the University of Alberta. Data from three additional observers were not used because they could not return for the second session. The main dependent measure used in the analyses was A′, a nonparametric measure of sensitivity (Grier, 1971; Pollack & Norman, 1964), although analyses of the percentage correct on positive and negative trials are presented for completeness. A′ can be interpreted as an estimate of the proportion correct that would occur if the experiment were run as a two-alternative forced-choice task.

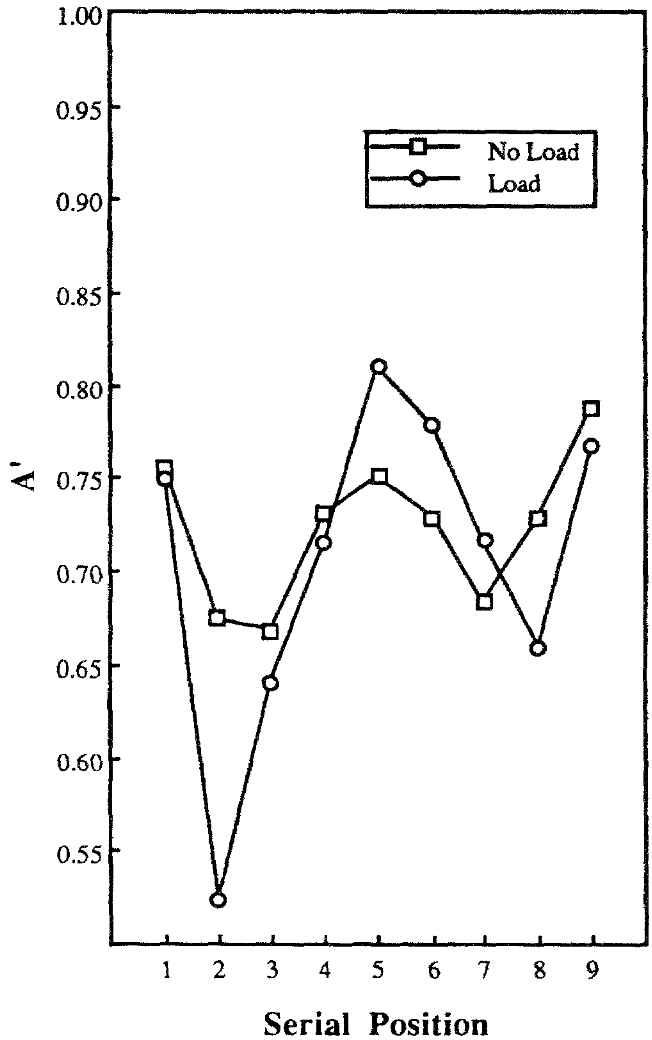

Fig. 1. Interaction between serial position and verbal load in Experiment 1

Results

The A′ results are shown in Table 1. Overall, there was no effect of stimulus duration, $F(2,16)<1$, and no effect of memory load, $F(1,8)<1$. However, there was a significant interaction between duration and load, $F(2,16) = 7.99$, $p < .005$. This interaction occurred because performance in the load condition improved from 50 to 100 ms duration, $F(1,8) = 6.36$, $p < .05$, while performance in the no-load condition showed no significant change from 50 to 100 ms, $F(1,8) = 2.39$. The proportion correct for positive and negative trials is also shown in Table 1. The pattern of results for proportion correct were precisely the same as for that for A′. There was no overall effect of memory load, $F(1,8)<1$, no effect of stimulus duration, $F(2,16)<1$, but an interaction between the two factors, $F(2,16) = 8.15$, $p < .005$. The difference between positive and negative trials was not significant and did not interact with any other factor.

A′ was also calculated separately for each serial position. Because serial position was undefined on negative trials, the overall proportion correct on negative trials in each condition was used as the correct rejection rate for all serial positions. The A′ analysis showed an effect of serial position, $F(8,64) = 6.22$, $p < .001$, an interaction between serial position and load, $F(8,64) = 4.28$, $p < .001$, and an interaction between serial position and stimulus duration, $F(16,128) = 1.76$, $p < .05$. (The analysis also confirmed the interaction between load and stimulus duration described above, $F(2,16) = 8.76$, $p < .005$.) The interactions with serial position are shown in Figures 1 and 2.

To gain further insight into these interactions with serial position, the data from the four left and the four right serial positions of the displays were collapsed to produce five eccentricities. Simple effects analyses were then performed at each of these five eccentricities. An effect of stimulus duration was found only at the ends of the array, $F(2,15) = 4.76$, $p < .05$; performance at this eccentricity improved as the duration increased. On the other hand, effects of load were found only at serial positions 2 and 8, i.e., one in from the ends of the array, $F(1,8) = 24.09$, $p < .005$, and, marginally, at the center of the array, $F(1,8) = 4.49$, $p < .07$. In other words, the presence of verbal load caused the low points in the W-shaped serial-position curve to become even lower, and the central high point to become somewhat

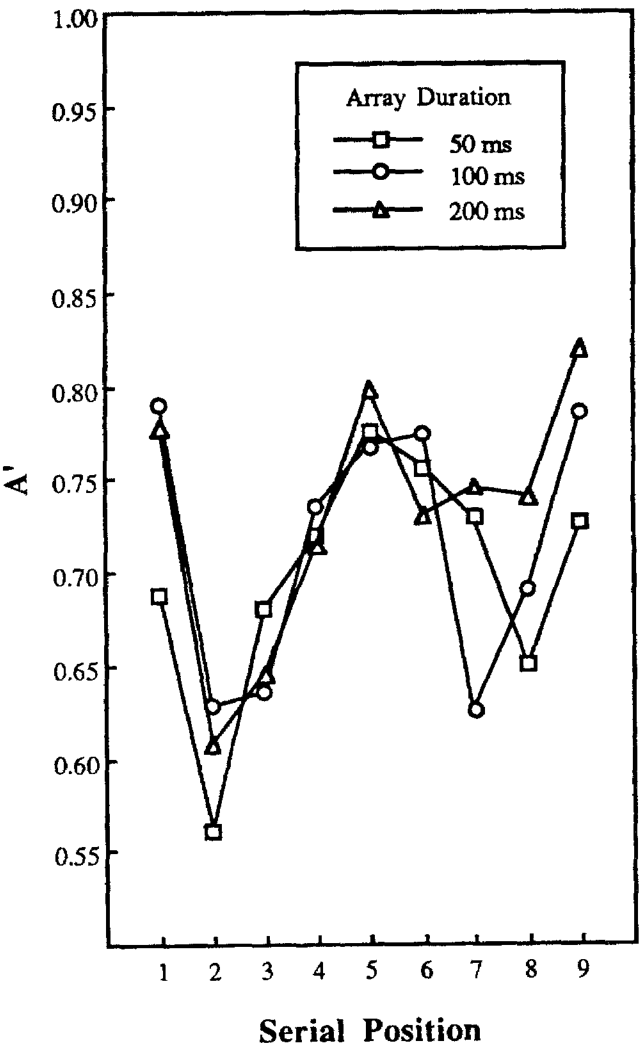

Fig. 2. Interaction between serial position and array duration in Experiment 1

higher. Thus, verbal load accentuated the serial-position effect.

An analysis was also performed on the percentage of correct positive trials at each serial position (shown in Table 2). Consistent with the A′ analysis, there was an overall effect of serial position, $F(8,64) = 5.52$, $p < .001$, and interactions between serial position and stimulus duration, $F(16,128) = 1.76$, $p < .05$, and between serial position and load condition, $F(8,64) = 4.00$, $p < .001$. These interactions had the same form as those found with the A′ analysis.

Discussion

The overall null result for verbal load is consistent with the work of Scarborough (1972), and suggests that the span of apprehension is not critically dependent on the involvement of verbal short-term memory. However, two theoretically important interactions with verbal load were found. The first was with array duration. When there was no verbal load, there was no significant variation in performance with array duration. But when subjects were asked to retain digits in short-term memory while trying to identify and retain the visual-display items, span was poorer at the 50-ms duration than at the longer durations. The second important interaction was with serial position. Performance at the difficult serial positions (i. e., positions 2 and 8 in Figure 1) was worse with verbal load than without verbal load. Both of these interactions have the same underlying form: when items were difficult to see, either because they were presented briefly or because they were masked by flanking items, performance was negatively affected by the presence of verbal load. Thus, both interactions are consistent with the view that verbal load interferes with the retention of perceptually difficult items.

In our account of this pattern of results, we assume that maintenance of the load items requires a certain amount of attention. Although verbal load may require articulatory processing and may reduce the available capacity of verbal short-term memory, these effects have no direct bearing on span-of-apprehension performance. Instead, we assume that verbal load affects performance because it requires attentional resources that might otherwise be devoted to processing difficult items in the array. In this view, the reduction of available resources will have little effect on items that are easy to identify; presumably, such items will be encoded automatically. Attentional resources will be crucial only for items that must be pieced together from fragmentary or degraded perceptual information. Thus, performance may be determined by a multiplicative relation between the availability of processing resources and the quality of perceptual information. Diminished perceptual quality will affect performance only when there are insufficient resources. This model is elaborated further in the General Discussion.

Scarborough (1972) found an interaction between verbal load and display duration that was qualitatively different from the one obtained here. In his results, increasing display duration improved performance when there was no verbal load, while in our results increasing display duration improved performance when there was verbal load. However, the two experiments used different ranges of display durations (50–200 ms in the present research and 200–500 ms in Scarborough's study), and it is likely that the two effects represent the operation of different mecha-

Table 2. Proportion correct on present trials in Experiment 1

	Serial position								
	1	2	3	4	5	6	7	8	9
Load condition (ms duration)									
50	.731	.429	.620	.636	.826	.810	.731	.556	.763
100	.922	.588	.620	.731	.858	.874	.731	.667	.874
200	.842	.461	.604	.763	.874	.794	.763	.715	.890
No-load condition									
50	.715	.540	.683	.747	.779	.779	.699	.715	.747
100	.794	.604	.556	.715	.715	.731	.493	.651	.794
200	.810	.715	.604	.620	.731	.683	.699	.779	.890

nisms. We have proposed that verbal load interferes with one's ability to process items from very brief displays, but this would be much less important given the range of exposures used by Scarborough. Scarborough, on the other hand, suggested that his exposure-duration effect occurred because subjects were able to transfer a few additional items to verbal short-term memory when there was no verbal load, and so improve their performance in relation to the no-load conditions. However, because verbal responses were never required in our span task, verbal short-term memory may not have been used at all in the present experiment, even in the absence of verbal load. Thus, the apparently discrepant interactions between verbal load and display duration can plausibly be attributed to differences in task and display parameters.

In addition to the interactions with verbal load, Experiment 1 also uncovered an interaction between serial position and array duration; accuracy for items at the ends of the arrays improved as the duration of the array increased. Our interpretation of this result is that performance at eccentric array positions is limited by available perceptual information, and hence can be aided by additional exposure time. Presumably, performance at internal array positions is limited primarily by factors other than available information (e. g., lateral interference), and so increasing the duration of the array has relatively little effect. This interpretation is consistent with the view that the effects of lateral interference and retinal eccentricity occur at different processing levels (Wolford, 1975; cf. Merikle & Coltheart, 1972).

Experiment 2

In Experiment 2, we tested whether serial position interacts with the processing and storage of items in visual working memory. If the serial-position effect is caused in part by some items being more difficult to maintain in visual working memory than others, then interfering with visual working memory should accentuate this effect. In other words, one would expect to find more pronounced serial-position effects whenever additional demands are made on visual working memory.

Visual working-memory demands were manipulated by the presentation of a visual suffix. A variety of studies suggest that irrelevant visual stimuli interfere with the contents of visual working memory even when it is strategically ill advised to attend to those stimuli. For example, Frick (1989) presented a series of visual items to be remembered, followed by either an irrelevant visual stimulus or an irrelevant auditory stimulus, and found that memory for the last visual item was impaired by the subsequent visual stimulus, but not by the auditory stimulus. We refer to these modality-specific effects of subsequent visual stimuli as *visual-suffix effects*. It seems likely that visual-suffix effects occur because the visual stimulus enters visual working memory involuntarily and displaces, or otherwise interferes with, the information being retained there. This view of the operation of visual working memory is consistent with the results of Phillips and Christie (1977); they found that when several visual displays were presented in sequence, memory for the details of the final visual display was quite good, even at long retention intervals, while memory for the earlier displays was much poorer. This pattern of results would occur if each succeeding visual stimulus displaced the prior information in visual working memory.

A visual-suffix effect in the span of apprehension is suggested by the results of Dixon and Twilley (1988). They compared auditory and visual targets in an experiment very similar to the present one and found better overall performance when the target was presented auditorily rather than visually. We suspect that this difference occurred because the presentation of the visual target item interfered with array items being retained in visual working memory. However, there are at least two reasons why this effect may not have been specific to visual working memory. First, Dixon and Twilley found a large difference between auditory and visual targets when the array and the target were presented close together in time, but a much smaller difference when the target was presented 1 s after the array. If the poor performance associated with the visual target was due to its interfering effects on visual working memory, one might have expected the effect to persist even at longer delays. Second, the task used by Dixon and Twilley required subjects to attend and process the visual-target item. Thus, the interference may have more to do with directing attention to a second visual display than with the displacement of information from visual working memory. Indeed, the model proposed by Dixon and Twilley for their results located the interference effect in the comparison process needed to decide whether the target was present in the array. In the present experiment, we used a visual suffix that was entirely irrelevant to the task. Thus, any effect of the suffix can be attributed specifically to its interfering effects on visual working memory rather than to other aspects of the task.

Experiment 2 was similar to Experiment 1 in that an array of letters was presented, followed by a single target item; the observer's task was to decide whether the target item was in the array. However, the target was presented auditorily in this experiment (cf. Merikle et al., 1971). There were two presentation conditions. In the suffix condition, an irrelevant visual item was presented between the presentation of the array and the auditory target, while in the no-suffix condition, no such item was presented. If the array is maintained in visual working memory and subsequent visual stimuli interfere with this store, performance should be better in the no-suffix condition.

The verbal load was also manipulated in Experiment 2. The results of Experiment 1 suggested that some of the effects found in visual working memory occur only when attentional resources are scarce. For example, an effect of array duration was found only in the verbal-load condition, presumably because in that condition there were fewer attentional resources available for processing degraded information in visual working memory. For the same reason, one might expect to find more pronounced suffix effects in Experiment 2 in the presence of verbal load.

Table 3. A′ and proportion correct in Experiment 2

	A′	Accuracy on present trials	Accuracy on absent trials
Load condition			
No visual suffix	.818	.803	.661
Visual suffix	.754	.768	.569
No-load condition			
No visual suffix	.775	.740	.637
Visual suffix	.763	.731	.669

Method

The task was similar to that used in Experiment 1. Subjects viewed a brief array of letters followed by a single target letter and subsequently had to decide whether the target was in the array. The results of Experiment 1 suggested that items near the edges of the array may have been difficult to identify, particularly at the shortest array durations. To reduce this problem, the array consisted of only seven items in Experiment 2. In the suffix condition, an irrelevant visual item was presented in the center of the screen 2 s after the presentation of the array and remained on the screen until the subject responded; no irrelevant items were presented in the no-suffix condition. In both conditions, the target was presented auditorily. As in Experiment 1, there was a load condition (in which subjects had to retain several digits for later recall) and a no-load condition. However, in an effort to make the load condition more demanding, subjects were asked to repeat four randomly chosen digits aloud for the duration of the trial. The visual-display conditions were generally the same as in Experiment 1. Auditory stimuli were produced by a Jameco JE520 Voice Synthesizer and presented over a loudspeaker at a comfortable listening volume.

The procedure on each trial was as follows. Subjects initiated each trial by pressing both buttons in a hand-held button box; the trial began 500 ms later. In the load conditions, four randomly chosen digits were first shown for 500 ms. The array was presented after an additional 1,500 ms. In the no-load conditions, the digits were not shown and the array was presented 500 ms after the trial was initiated. The array consisted of seven randomly chosen consonants (excluding B, G, J, Z, M, and V) and was presented for 50 ms. The target was presented at an SOA of 2,500 ms in the no-load conditions and 2,000 ms in the load conditions.

In addition to the suffix and no-suffix conditions, subjects also participated in a third presentation condition in which the target was presented visually. This condition effectively replicated the display conditions used in Experiment 1. The results for this condition, as predicted, were generally the same as those found for the suffix condition and will not be discussed further.

Half of the subjects participated in the load condition and half in the no-load condition. Within each of these groups, all of the subjects performed two blocks of trials in each of the three target conditions. Each block began with 10 practice trials followed by 42 randomly ordered test trials. Half of the trials were present trials in which the target letter matched one of the letters in the stimulus array, and half were absent trials. On present trials, the target appeared three times in each serial position. (Six subjects received blocks of 56 trials, but this was reduced because a few of these subjects showed signs of fatigue by the end of the session). At the end of each block of trials, observers were told about their accuracy.

Each session began with a familiarization drill in which subjects viewed the letters as they would be seen in the experiment while simultaneously listening to the letters being produced by the voice synthesizer. Subjects then performed three trials of each target type under the supervision of the researcher. Subjects were also given three practice blocks of 20 trials each, one block in each target condition. In the load condition, the practice blocks were performed at the beginning of the session, while in the no-load condition each practice block was performed just before the first test block of that condition. Subjects performed one block of each of the three target conditions first, and then performed the three conditions in the opposite order. Across subjects, the six possible orders of the conditions were used equally often. The entire session lasted about an hour.

Twenty-four undergraduates at the University of Alberta served as paid volunteers; data from one subject in the no-load group were not used because of near-chance performance in one condition.

Results

The overall A′ results are shown in Table 3. Performance in the load conditions was better when there was no visual suffix, $F(1,11) = 9.80, p < .01$, but no such effect was found in the no-load conditions, $F(1,10) < 1$. This led to a marginal overall effect of suffix, $F(1,21) = 4.03, p < .06$, and an interaction between the presence of the suffix and verbal load, $F(1,21) = 5.10, p < .05$. Consistent with this analysis of the A′ data, an analysis of the proportion correct showed an interaction between verbal load and presence of the visual suffix, $F(1,21) = 6.30, p < .05$, and a marginal effect of suffix condition, $F(1,21) = 3.05, p < .10$; (see Table 3). Mean accuracy was higher on present trials than on absent trials, $F(1,21) = 12.36, p < .01$.

Verbal load produced no overall decline in either A′ or correct proportion; in fact, performance in the verbal-load conditions was somewhat better than that in the no-load conditions. A slightly shorter delay was used in these conditions between the array and the target, and perhaps the detrimental effects of verbal load were offset somehow by this small difference in procedure. Alternatively, the failure to find a significant decrement in the load conditions may have been due to a statistical Type-II error; because different subjects participated in the load and no-load conditions there was relatively little power for this type of comparison.

A′ at each serial position is shown in Figure 3. As in Experiment 1, A′ was calculated at each serial position by using the overall percentage correct on negative trials in each condition as the correct rejection rate. There was a clear effect of serial position, $F(6,126) = 5.62, p < .001$. There was also a significant effect of suffix condition, $F(1,21) = 5.88, p < .05$. As in the overall analysis, the suffix effect was restricted to the verbal-load condition, leading to an interaction between suffix condition and verbal load, $F(1,21) = 4.81, p < .05$.

As can be seen in Figure 3, the W effect of serial position in the verbal-load conditions was much stronger when there was a visual suffix than when there was no visual suffix. When the verbal-load condition was analyzed separately, there was a significant interaction between serial position and suffix, $F(6,66) = 2.26, p < .05$; no such interaction was found in the no-load condition, $F(6,60) < 1$. However, the three-way interaction among serial position, suffix, and verbal load failed to reach significance. To pursue the apparent interactions with serial position more fully, the positions on the left and right sides of the display were averaged, and analyses were performed at each of the resulting four eccentricities. An interaction between suffix and load was found in positions 2 and 6, $F(1,21) =$

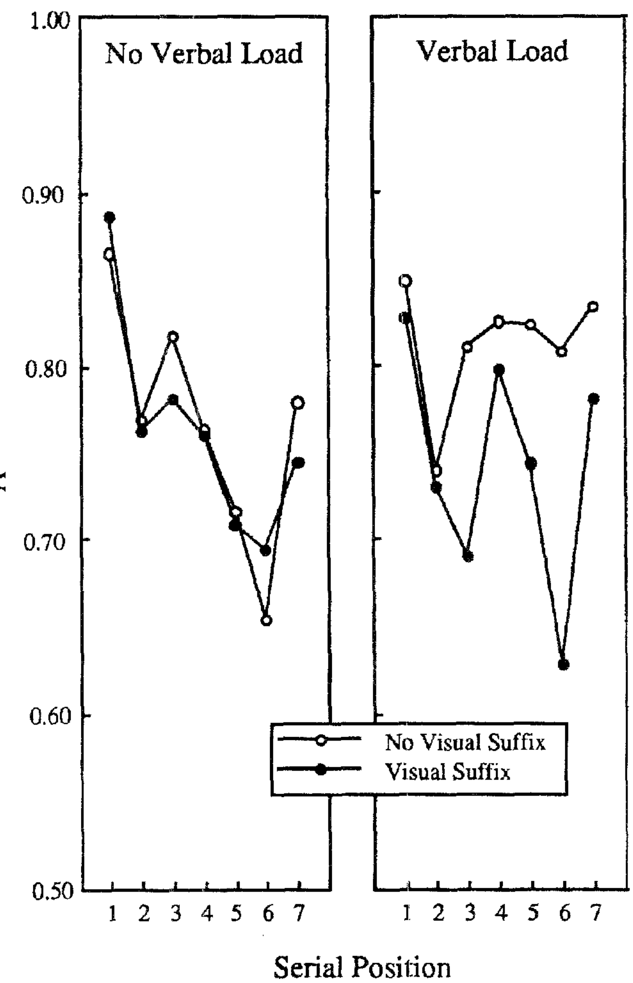

Fig. 3. Interaction between presence of a visual suffix, serial position, and verbal load in Experiment 2

5.41, p <.05, and marginally, in positions 3 and 5, $F(1,21) = 3.00$, p <.10. An overall effect of suffix was found in positions 3 and 5 as well, $F(1,21) = 7.43$, p <.05. No significant effects were found at the other two eccentricities.

An analysis of the serial-position effects for proportion correct on present trials produced similar results (see Table 4). There was a significant effect of serial position, $F(6,126) = 6.27$, p <.01, and an interaction between serial position and load, $F(6,126) = 2.42$, p <.05.

Discussion

Experiment 2 produced two main results: First, in the verbal-load conditions, performance was worse when a visual suffix was presented than when no suffix was presented. Second, the serial-position effect in the verbal-load conditions was more pronounced when a visual suffix was presented. Neither of these effects occurred when there was no verbal load. These results are qualitatively similar to those found in Experiment 1. In both experiments difficult items were made more difficult by the presence of verbal load. In Experiment 1 items were difficult when they were presented for very brief durations and when they were masked by flanking items. In Experiment 2 items were difficult when they were followed by a visual suffix. This had the result of reducing performance and making the serial-position effect more pronounced, but only when there was a concurrent verbal load. We propose that verbal load has these effects because it requires a certain amount of attention, and that there is a multiplicative relation between available resources and the quality of perceptual information that can be maintained in visual working memory. Thus, performance suffers only when there is both a relative lack of available resources and an interfering visual stimulus.

Table 4. Proportion correct on present trials in Experiment 2

	Serial position						
	1	2	3	4	5	6	7
Load condition							
No visual suffix	.861	.653	.778	.847	.833	.778	.861
Visual suffix	.875	.722	.694	.847	.792	.611	.833
No-load condition							
No visual suffix	.905	.739	.818	.731	.663	.568	.833
Visual suffix	.936	.742	.773	.750	.629	.583	.701

General discussion

The results of these experiments can be summarized as follows: In Experiment 1 performance increased as the duration of the array presentation increased, but only when under verbal load. And in Experiment 2 performance declined with the presentation of a visual suffix, but only under verbal load. Both of these effects failed to obtain when verbal load was absent. Related effects were found in the serial-position analyses. In Experiment 1 the usual W-shaped serial-position effect was larger with verbal load, and performance at the ends of the array improved with array duration. In Experiment 2 the serial-position effect was more pronounced when verbal load was combined with the visual suffix. This pattern of results is generally consistent with the idea that verbal load reduces the available processing resources and that there is a multiplicative relation between available resources and the quality of the perceptual representation in visual working memory. A specific model of the span task is described below to account for these results as well as for other findings in the literature.

In our model, we assume that an automatic identification process operates on the visual input. This process operates in parallel and without requiring attentional resources. Similar assumptions about automatic identification have been made by Dixon (1986), Duncan (1980), Gardner (1973), and others. However, the identification process is unlikely to be perfect and may be subject to data limitations related to the quality of the perceptual input. That is, some of the time the identification process will produce a correct item identity; at other times the output of the identification process will be incomplete or fragmentary. In either event, we assume that the output of this identification process is retained in visual working memory. Thus, shortly after a brief array presentation, visual working memory will contain some number of item identities plus collections of visual features corresponding to items that were not completely identified.

Although visual information enters visual working memory automatically, we assume that this information will decay quickly unless rehearsed, and that this rehearsal process requires attentional resources. In this sense, our concept of visual working memory is similar to the concept of working memory and the visuospatial scratchpad discussed by Baddeley (1986). The crucial assumption needed to account for the present results, though, is that some items are more difficult to rehearse than others. In particular, collections of features that represent the output of an incomplete identification process will require more resources for their retention than items that were completely identified. In other words, items that are hard to see and identify to begin with will be hard to retain in visual working memory over time.

The model predicts the multiplicative relation found between display quality and verbal load in Experiment 1. We assume that verbal load requires a certain amount of attention that could otherwise be directed to maintaining array items in visual working memory. The items that would suffer most from this reduction in available resources would be those not clearly identified initially. In particular, items in the interior of the array would suffer more than items at the ends of the array, and items at the periphery would suffer more than items in the center of the fovea. Thus, one would expect an enhanced serial-position effect with verbal load, as was found. Similarly, 50-ms visual displays may be more difficult to see than longer displays, and this difficulty would be more pronounced when there are fewer attentional resources. This accounts for the finding that a positive effect of array duration was found only with verbal load.

A similar explanation can be given for the interactions with visual suffix found in Experiment 2. In this case, we assume that the visual suffix displaces or otherwise interferes with information stored in visual working memory. As in Experiment 1, verbal load may reduce the available resources used for maintaining items in visual working memory, and the interfering effect of a suffix would be more pronounced when there are fewer resources. Thus, the model can account for the poorer performance that occurs when the visual suffix is combined with verbal load. When this interfering effect occurs, it is most likely to affect items that were difficult to see at the outset. Thus, the poorer performance found with the visual suffix and verbal load is accompanied by an enhanced serial-position effect.

The proposal that visual working memory is limited in terms of the maintenance of information rather than in terms of its total capacity allows one to reconcile the apparent perceptual limitations on the span of apprehension (discussed by Wolford, 1975, and others) with the results obtained with partial reports, which suggest that almost all of the items are perceptually available shortly after the display. We propose that some items will be clearly identified and coded in their entirety in visual working memory. However, information about other items will be only partial or fragmentary. If attention can be directed to a fragmentary item immediately (as would be the case if they were cued in a partial-report task), then it is likely that the visual system would be able to identify the item correctly and maintain it for later report. On the other hand, if report of a fragmentary item is delayed, then it would have to share resources with all of the other items in the display. A fragmentary item would suffer more under such circumstances than other items that are coded in an intact fashion, and would be more likely to be lost before the items could be reported. In other words, a serial-position effect is found in span of apprehension because those items that are difficult to perceive initially will also be difficult to maintain in visual working memory.

A similar account can also be offered for the results of Wolford and Hollingsworth (1974b). In their study the span of apprehension was reduced by the visual array being offset to the left or the right of fixation so that items on average were presented at more peripheral locations. We hypothesize that this manipulation leads to greater number of items that are encoded in a fragmentary or incomplete fashion. Because such items require more resources to be maintained in visual working memory, the total number of items that can be maintained with a fixed-resource capacity would be reduced. Thus, the effects of array eccentricity on span of apprehension reflect the varying resource demands of different item presentations: items presented at the periphery require more processing resources to be maintained in visual working memory than items presented in the fovea.

In sum, the model predicts that variables that affect the quality of information and variables that affect the availability of resources in visual working memory interact in determining the number of items that can be maintained. In particular, small decrements in the quality of information and available resources may combine to produce sizable decline in overall span, even though neither type of variable on its own may produce a discernible effect. In the present experiments we assume that the verbal-load task produces a decrement in the resources available for the maintenance of items in visual working memory. We also assume that several different variables affect the quality of available information. These include the duration of the array, the lateral interference from neighboring array items, and the presence of a visual suffix. In Experiments 1 and 2 these three variables led to a larger effect on performance when they were combined with a verbal-load task than when they were manipulated in isolation.

We conclude that the span of apprehension is related to the maintenance of information in visual working memory. However, span should not be viewed as the product of an absolute capacity limitation, but rather as the interaction between the attentional requirements needed to maintain items in visual working memory and the data limitations imposed by a brief visual presentation.

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