Short-Term Memory in Vision

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Experiments are performed that demonstrate some of the functional properties of short-term storage in the visual system, its decay, readout and erasure. Results indicate that the visual process involves a buffer storage which includes an erasure mechanism that is local in character and tends to erase stored information when new information is put in. Storage time appears to be of the order of one-quarter second; storage capacity is more difficult to assess.

I. INTRODUCTION

There can be little doubt that eye movements play an important role in the perception of form, and that perceptions of complicated visual fields are built up from information gathered during many fixations of the eyes. But eye movements over a complicated visual field are unpredictable from subject to subject and from time to time with the same subject. They may therefore be an annoying source of variability in perceptual experiments, and experimenters frequently find it desirable to eliminate them. This is usually done by using a tachistoscope, a device for presenting brief exposures of visual material. The position of the eyes is kept fixed at the crucial time by having the subject fix his eyes *before* exposure of the material, and by using exposures sufficiently brief that the subject cannot change his fixation during the exposure. To accomplish this, exposure times must be less than the reaction time of the eye for a change of fixation (150–200 milliseconds). Actual measurement in a tachistoscopic situation has shown that exposures of 100 milliseconds or shorter satisfy this purpose.[1]

At first thought, it may seem unreasonable to study visual perception under the peculiar condition of tachistoscopic experiments. Some question might be raised about whether data obtained in this way can be generalized to natural perceptual situations. It can be argued, however, that in a very real sense the tachistoscopic situation is not an unnatural one. For it is well established that, in scanning pictorial or printed material, the eyes do not take in information continuously (Ref. 2, p. 493). They fixate first on one point and then move rapidly to another. The fixations are relatively long, but the movements between fixations are so quick that they smear the image drastically during the motion. Thus, normal vision involves the processing of discrete exposures very much like those presented in a tachistoscope. It has been shown, in fact, that reading performance is better if the necessity of moving the eyes is eliminated by presenting reading material serially by means of a tachistoscope.[3]

To anyone who has ever seen objects illuminated briefly by a spark or other kind of brief flash it is evident that the visual impression of the illumination lasts longer than the flash. Even a millisecond flash seems to last a noticeably long time. Because of this persistence, writers on perception, particularly tachistoscopic perception, have assumed the existence of some kind of short-term storage in the visual system. This is implied in their use of such terms as positive afterimage, retinal persistence, persistence of vision, etc., in interpreting tachistoscopic performance. But little work has been done to characterize the functional properties of the storage, its decay, readout and erasure. In this paper we will discuss some of the older studies that bear on these matters and report a few experiments that demonstrate some properties of this visual short-term storage.

II. MEMORY EXPERIMENT

A very old tachistoscopic experiment is the span-of-perception experiment. Its aim is to determine the maximum number of objects a person can take in at a glance, the objects being dots, letters, digits, words, etc. Typically, the experimenter makes up cards having different numbers of items on them. Starting with cards having one item, he keeps increasing the number of items presented until the subject begins to make errors. The perceptual span may be taken to be the maximum number of items that the subject can report perfectly. More usually, the criterion used is the number of objects reported correctly 50 per cent above chance.

Spans of perception measured by different investigators are surprisingly consistent considering the wide range of conditions under which these spans have been measured. The span for letters or words[4,5] is $4\frac{1}{2}$ to 5 and for dots[5,6] about 8. What limits the span of perception? Of course, anything that affects legibility — brightness, contrast, sharpness, etc. — will under some conditions affect the span. But once reasonable legibility is obtained, increasing the brightness and contrast and sharpness does not improve performance. Under conditions of good legibility the limitation is elsewhere.

Two possibilities suggest themselves. First, the span may be limited by the *capacity* of the visual storage. It may be that, as the number of items put into the storage is increased, resolution of the individual items is destroyed. The other possibility is that resolution of the storage is perfectly adequate for numbers of items of the order used in span of perception experiments, but that the *storage time* is too short; i.e., the subject does not have enough time to read more than a few items into his more permanent memory before the decay of the short-term storage.

Selecting between these alternatives presents something of a problem. How does the experimenter determine how many items a subject can store visually if the subject, as shown by span of perception experiments, can report correctly only a limited number (4 or 5) items? This difficulty was circumvented by Sperling[7] who, instead of requiring that his subjects report on the whole of a complicated tachistoscopic presentation, had them report on only a part. He exposed briefly three rows of four randomly chosen letters each. Then, after a variable delay, he presented a tone signal of either high, middle or low pitch which indicated to the subject that he was to report on the upper, middle or lower row of letters — whichever was indicated by the tone. Since the subject was not familiar with the arrays of letters and was not given the instruction tone until the visual stimulus was turned off, he had, in effect, to store the whole array. By this method Sperling was able to show that subjects can store as many as 9 letters of a 12-letter array — and even more when arrays having more letters are used.

The experiment to be described, although conceived independently of Sperling, is of essentially the same form as his. The essential difference lies in the use of a *visual* signal to designate the part of the array to be reported by the subject. This has the virtue that it assures that the array and signal are transmitted to wherever they are processed in the brain at approximately the same rate. It is known that the reaction time to a light is significantly longer than the reaction time to a tone (Ref. 2, p. 16).

A 2 × 8 array of randomly chosen letters is exposed for 50 milliseconds. Then, after a variable delay, a black bar marker is presented for 50 milliseconds either above one of the letter positions of the upper row or below one of the letter positions of the lower row. The subject's task is to name the letter designated by the marker. A typical array and bar marker are shown in Fig. 1. A black circle that is used as a marker in a second experiment to be described later is also shown. The subject, of

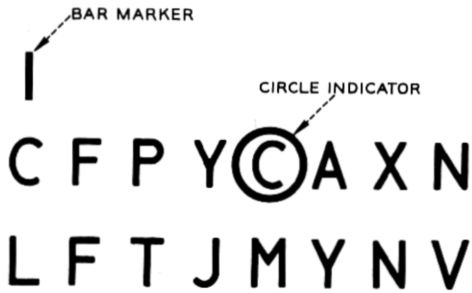

Fig. 1 — Typical array of letters, bar marker and circle indicator.

course, never knows before a given trial which letters will appear in the array, and which of the 16 letter locations will be called for by the marker. Thus, in order to perform well, he is required to store the array until the appearance of the marker. The sequence is illustrated in Fig. 2.

A uniform field of 70 foot-lamberts was maintained constantly throughout the experiment, and the letters and marker appeared black against this background. This test field subtended a visual angle of 4 degrees vertically by 5 degrees horizontally at the viewing distance of 5 feet. It had a small dark fixation point in the center. Surrounding this field was a larger field, 12 degrees on a side, having a luminance of 30 foot-lamberts. Each letter subtended one degree vertically by one-half degree horizontally. The black of the letters had a brightness of less than one foot-lambert.

2.1 *Procedure*

At the beginning of each session subjects were given two or three minutes to adapt to the bright screen. They were then given two warm-up trials with arrays that were not used in the experiment proper. On each trial the subject was given a ready signal and enough time to fix his eyes on the fixation point at the center of the screen. When fixated, he would signal the experimenter and the array and marker were then exposed. The subject was given as much time as he needed to make his response, but was encouraged to use his first guess if he was in doubt. He was given the correct answer after each trial.

During each session 128 array-marker pairs were exposed, covering each of the 16 positions at each of 8 time intervals between array and marker. The same order of presentation of the 128 arrays was used in each session of the experiment, but the time interval and marker posi-

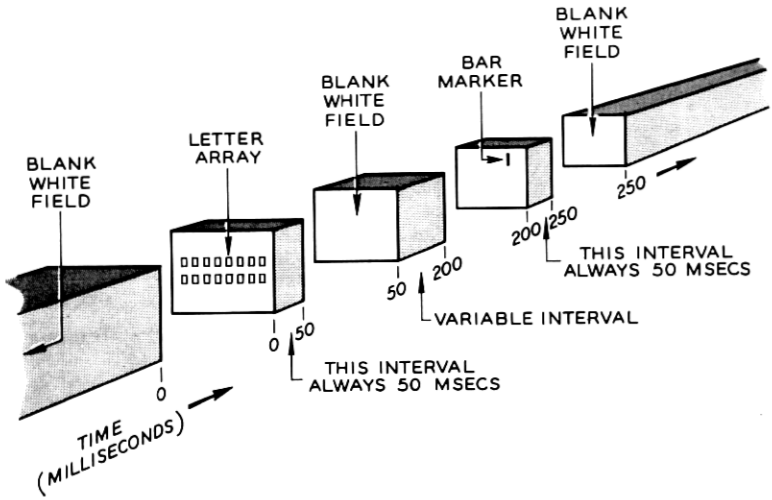

Fig. 2 — Sequence presented in a typical trial.

tions were varied randomly, with the restriction that successive groups of 16 arrays each contained a marker in each of the 16 positions. Three sessions were run with each of the three subjects.

2.2 *Apparatus*

The tachistoscope used is that designed by Nielsen,[8] which uses multi-channel television generating equipment and a set of gates controlled by timers for presenting a sequential display of three pictures on a single picture monitor. Each picture can be displayed for a preset time interval of $N/60$ seconds, where N is a number of television fields from 1 to 99. Since all parts of a picture are not exposed simultaneously and a particular point on the monitor is illuminated for only 20 microseconds, exposure times are taken from the time a particular point is first scanned to the time the same point is scanned in a new picture. An exposure of 50 milliseconds, preceded and followed by a white field, is illustrated in Fig. 3, which also shows the brightness of a point near one of the letters. Interlace is ignored since the center-to-center separation of the scanning lines subtended less than one-half minute of arc at the observer's eye.

The time between the onset of an array and the onset of a marker is never an integral number of fields, owing to the fact that the marker does not appear in the same part of the vertical scan as the letter it designates. This small error has been ignored, since it is only -3 milli-

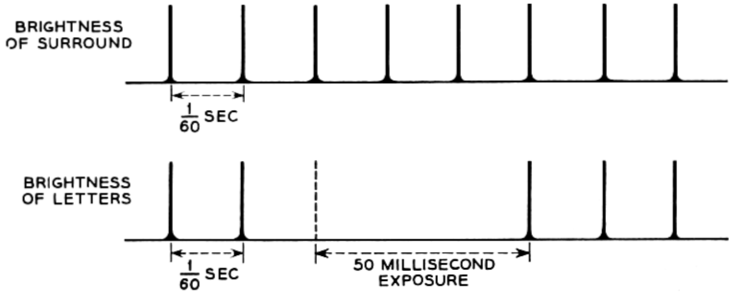

Fig. 3 — Brightness of letter and surround for exposure of 50 milliseconds preceded and followed by a white field.

seconds if the marker falls above the array and +3 milliseconds if the marker falls below.

2.3 *Results*

The results for the three subjects are shown in Fig. 4. The abscissa is the time in milliseconds between the onsets of array and marker. The ordinate is the per cent correct, corrected for chance on the assumption that the subject perceives correctly a certain percentage of the time P_p and guesses randomly from the 26 possible letters when he does not perceive correctly. On this assumption, the measured per cent correct $P_M = P_p + (1 - P_p)\ (1/26)$, which yields the plotted P_p's. Estimates of the standard error of these points, which are a function of the number of trials (48) and the per cent correct, range from 0.07 at 50 per cent to 0.06 at 20 and 80 per cent correct.

The vertical lines through zero and 50 milliseconds represent the onset and offset of the arrays. Negative time means that the marker came before the array. The point at zero time was taken after the rest of the experiment was completed because it required modification of the apparatus.

2.4 *Discussion*

Although it might be assumed that this experiment yields a reasonably good description of the time-decay of the short-term visual storage, the curves obtained cannot be said to represent this decay for two reasons. First, the true storage would be expected to decay to zero for long enough time intervals. But these results decay to a final level of about 35 per cent for two of the subjects and 25 per cent for the third. Second, because the process of detecting a marker and reading a letter

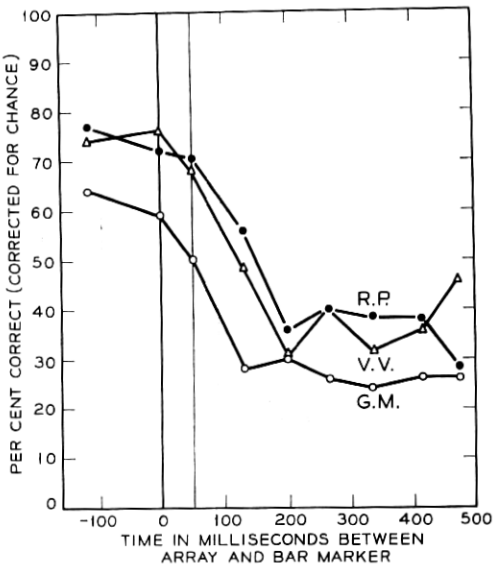

Fig. 4 — Results of memory experiment; "R.P.," "V.V." and "G.M." identify the three subjects participating.

undoubtedly takes time, the measured performance suggests a storage time that is shorter than the true storage time.

The fact that the measured decay curves do not fall to zero suggests that the measured performance contains components of a more permanent memory, as well as the short-term memory component that we would like to measure. In this context, the 25 to 35 per cent final performance level (which represents 4 to 5.6 letters) is attributed to what the subject has read into his more permanent memory.

Maximum performance measured when the marker preceded the array is 65 to 80 per cent. It is obvious, of course, that, if the marker preceded the array by a long enough time, performance would reach 100 per cent. Why, then, doesn't performance reach 100 per cent? The reason is *not* that some letters are outside the fovea, since individual letters exposed in any of the 16 positions of the array are clearly legible. The explanation seems to lie, rather, in the fact that letters in some positions, although perfectly legible by themselves, are not legible in the context of the array. This finding is illustrated by the plot of performance as a function of position shown in Fig. 5. The numbers 1 to 8 represent, from left to right, the positions on the upper line of the array, and 9 to 16 the positions on the lower line. The percentage is based on the pooled

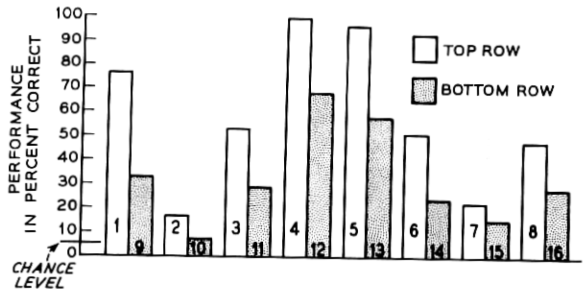

Fig. 5 — Performance by position in array, three-subject average.

data of the three subjects, each point being based on 72 trials taken across all time intervals. All subjects show the same distribution, in which performance is better at the center and ends, and poorer in between. Performance on the upper line is consistently better than performance on the lower.

2.5 *Summary*

In summary, the following can be stated:

1. The visual system can store information for longer than 130 to 200 milliseconds.
2. This storage can be tapped selectively on a signal given by the experimenter.
3. Resolution of the storage — or ease of reading-out — is disturbed when too much data is put in. Sixteen letters in a 2 × 8 matrix is enough to demonstrate this effect.
4. This disturbance does not affect all items of such a stored array equally. It disturbs the center and end items least and those in between most.
5. As an exercise, we estimated the amount of information in the store when the bar marker follows immediately after the array, and obtained the figure of 37 bits for the poorest subject and 54 bits for the other two subjects.

III. ERASURE

If persistence were the only property of the visual storage, it would be difficult to understand how we see at all in our normal, continually changing environment. A storage process normally also involves erasure, to assure that old information is out of the store before new information is put in. Otherwise, new information and old would be inextricably merged in the store. The experiment to be described deals with the erasure properties of the visual storage.

The procedure in this erasing experiment was almost identical to that of the memory experiment just described. The same subjects were used, and the same arrays of letters were presented in the same sequence. The essential difference between the two experiments was in the form of the marker used. In the first experiment the marker consisted of a vertical bar pointing to the letter; in this experiment it consisted of a black circle surrounding the letter, as was illustrated in Fig. 1. Such a circle produces a curious effect upon the letter if the time delay between array and circle is chosen properly. This effect we call *erasure.*

3.1 *Results*

Fig. 6 permits a comparison of the performance by each of our subjects in the bar marker experiment with his performance in the circle experiment. The curves of all three subjects start at a relatively high level, ranging from 70 to 80 per cent, drop sharply to a minimum, ranging from 10 to 20 per cent and rise slowly to an intermediate level of 25 to 40 per cent.

When the circle precedes the array or follows immediately after, performance in the erasure experiment is not greatly different from performance in the first experiment. However, when the circle is delayed by 100 milliseconds, the difference between the curves is quite large. Then, with still longer time delays, performance in the circle experiment rises slowly until it reaches approximately the values obtained in the first experiment. Thus, the curves begin together and end together, with performance in the "circle" experiment significantly poorer between.

3.2 *Discussion*

This experiment shows how a later visual stimulus can drastically affect the perception of an earlier one. This backward-in-time action of the circle implies that the first stimulus is delayed with respect to the second, or, more precisely, that the first stimulus is stored. The process involves more than simple delay, since, as shown by the first experiment, the subject has access to the information during the delay.

The question arises as to why the circle has such a damaging effect on the letters and why the bar does not. The answer lies in their relative distance from the letter. In preliminary experiments it was found that,

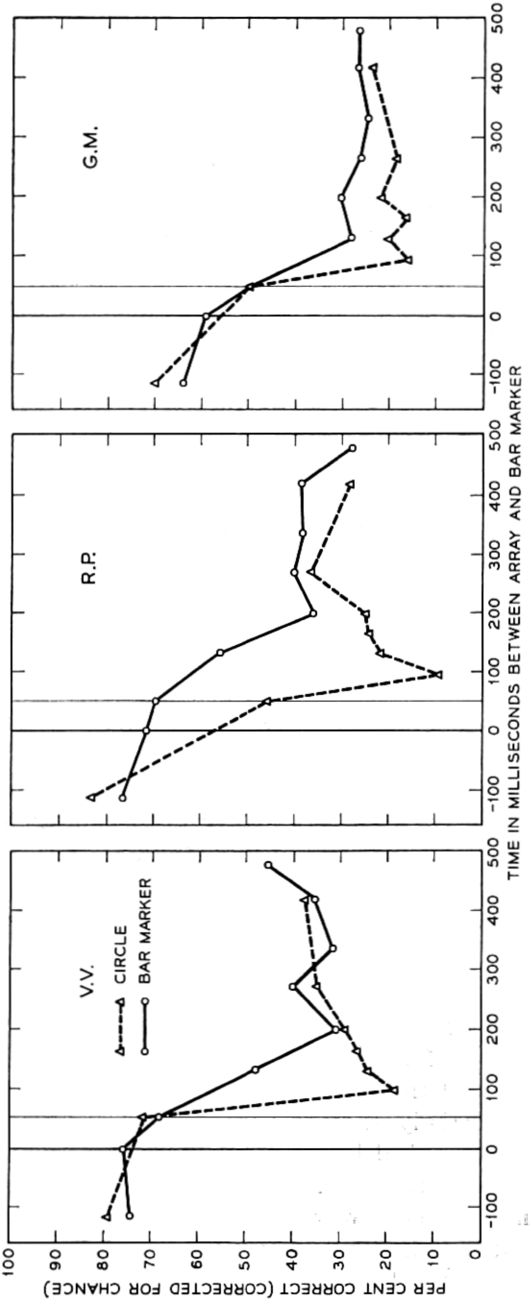

Fig. 6 — Results of erasure experiment compared to those of memory experiment.

when the bar was close to the letters, those parts of the letter near the bar were strongly disturbed. The bar was therefore placed far enough away from the letters to avoid this effect. All parts of the circle, however, are close to the letter.

One can conceive of the observed action of the circle on a preceding letter in many different ways. It is possible, for example, that the main effect on the letter is a "stopping in time", i.e., a quick substitution of the circle for the stored letter. Such a process could function as an erasure mechanism, since it would assure that new and old information are not confused in the store. It is conceivable, on the other hand, that the effect of the circle on the letter is of a different kind. Perhaps the disturbance is a result of the kind of mixing or averaging process that an erasure mechanism seeks to avoid, or perhaps the effect of the circle is primarily to reduce the brightness or contrast of the letter.

We are inclined to reject the latter alternatives. The observed effect is clearly *not* due to averaging in time, for if the circle and the letter it surrounds are presented simultaneously, the legibility of the letter is hardly affected at all. Yet this is just the condition for which averaging should produce the most damaging effect. With regard to the possibility that the circle affects the brightness or contrast of the letters we can say nothing conclusive. Introspectively, however, a change in brightness or contrast does not appear to be the primary effect.

The view that the second stimulus limits the time available for reading-out is more attractive than the other possibilities for several reasons. First, the rise found in the erasure curve with increasing delay of the circle after 100 milliseconds is consistent with the idea that increased delay of the circle allows more time for readout. A second reason for believing that the effect of the circle is primarily to limit readout time stems from our observation that the lowered performance obtained when the circle follows the letter is not independent of the number of letters involved. If a single letter is exposed in any one of the sixteen positions of the array and a circle is presented with a 100-millisecond delay — this is the delay that yields the poorest performance on our curves — this letter will be read correctly by our subjects 100 per cent of the time. On the other hand, if we expose four letters — which can ordinarily be reported perfectly — followed by the circle with this same 100-millisecond delay, performance is disturbed dramatically. Thus, we believe that the effectiveness of the circle in disturbing performance is related to how much reading has to be done before the circle appears. If only one letter must be read, the circle does not affect performance measurably because, according to this interpretation, the subject has

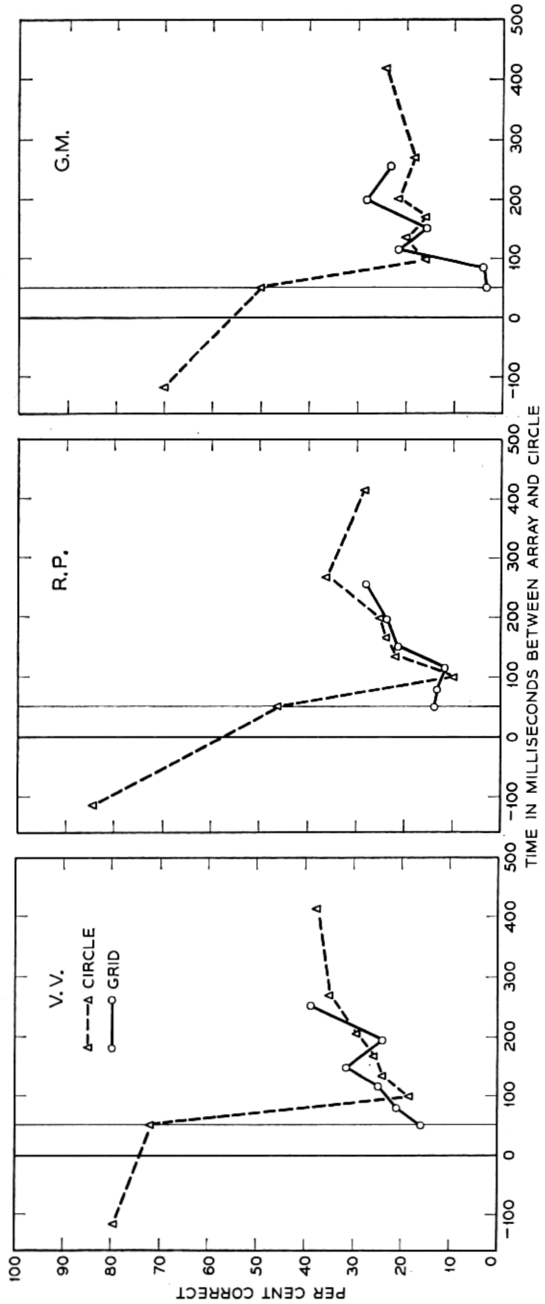

Fig. 7 — Results of erasure experiment, using circle and grid.

enough time to read the letter before the circle appears; if many letters must be read, the subject will not have enough time to read all of the letters before the circle appears. It is then likely that the circle will erase the letter it follows before it is read. Our final reason for thinking that the circle limits the time available is an introspective one. We find that a briefly exposed letter followed by a circle — even when it is seen as perfectly as it is when a single letter is exposed — seems to persist for a much shorter time than it does when it is not followed by a circle.

We are therefore inclined to say that the effect of the circle is to remove previously stored information. On this interpretation, the observed increase in performance with increasing delay is attributed, not to loss of erasing effectiveness of the circle, but to the increased time available for readout.

In the light of the above, the shape of the erasure curve may be interpreted as follows:

1. High performance when the circle follows immediately after the array is due to simple temporal averaging in the visual system. This results in array and circle being effectively superimposed, which does not significantly affect legibility.

2. Decreased performance at slightly longer delays can be attributed to the change from the superposition condition to the erasure condition.

3. The slow rise from the minimum with further increases in delay of the circle is attributable to the increased time available for the subject to read the letter before it is erased. At still longer times, when performance is about the same as in the bar experiment, the circle no longer erases but acts as a marker. This suggests, as outlined in the discussion of the first experiment, that performance at times longer than 200 milliseconds depends not on the contents of the short-term storage at that time, but on the number of letters that had been read into the permanent memory before that time.

The suggestion that two closely timed stimuli are perceived as being superposed is testable. In what was essentially a repeat of the experiment just described, we substituted a circle filled with grid lines for the unfilled erasing circle. When simple superposition holds, such an "eraser" should be much more interfering than a simple circle. The results are shown in Fig. 7.

The dashed lines are plots of the results obtained using an unfilled circle. The solid lines give the results obtained with the filled circle. It is seen that for delays longer than 100 milliseconds the difference between the two curves is small; while for delays of less than 100 milliseconds, the difference is large. This confirms that the disturbing effect

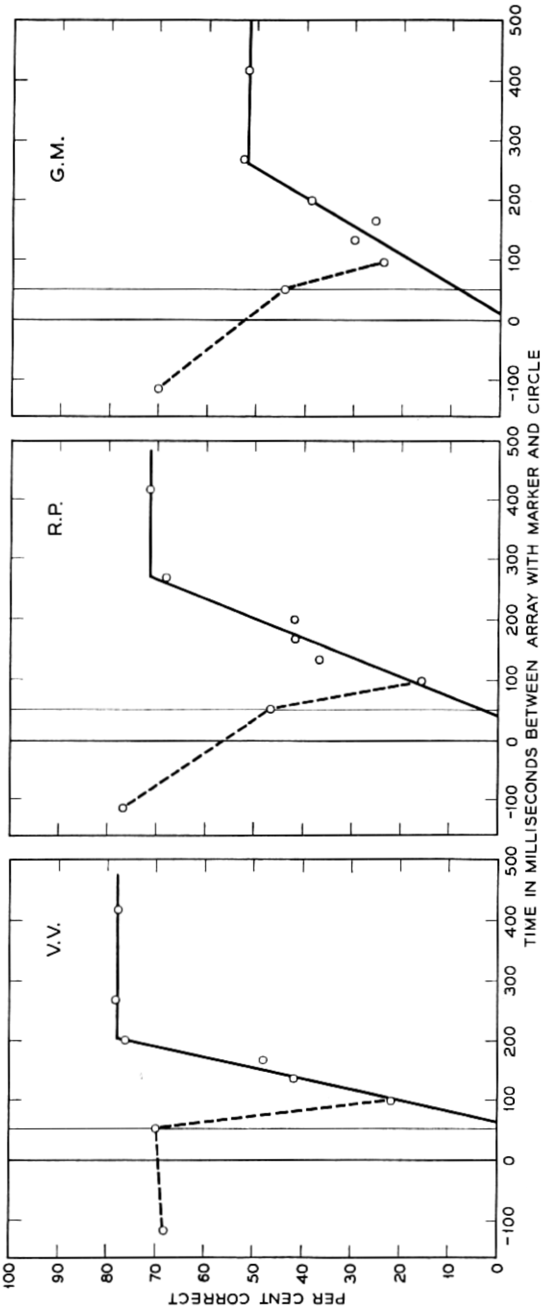

Fig. 8 — Results of readout experiment.

of a later stimulus on a preceding one may be of at least two varieties: the superposition type, which is understandable in terms of averaging; and the other effect, which we have called erasure.

It should be mentioned that preliminary work has been done in which an array of eight letters is presented to one eye and the circle delivered to the other. It is found that erasure occurs under these conditions although it has not yet been determined how this binocular erasure compares with monocular erasure.

IV. READOUT

As we have already pointed out in discussing the bar-marker experiment, the process of detecting the presence of a marker and reading the marked letter undoubtedly takes some time. If the time required for this process could be measured, we would be able to correct the decay characteristic obtained in the bar marker experiment for this time and have a more accurate idea of the duration of the storage. A method for measuring this time is available provided that our conclusions about the action of the circle in erasing a letter are correct. Suppose we present simultaneously an array and a bar marker pointing to one of the letters in the array. Then, a short time afterwards, suppose we present an erasing circle around the marked letter. If the circle indeed removes the marked letter from the subject's storage, his performance under these conditions will measure how well he can detect the marker and read the letter when given only the time interval between the onset of the array and marker, and the onset of the circle. Such an experiment was performed, in fact, using the same subjects and experimental conditions as before.

4.1 *Results*

The results appear in Fig. 8. The abscissa is the time between the onset of the array–bar-marker combination and the onset of the circle. The three curves are similar in form. It is seen that when the circle follows by more than 100 milliseconds performance rises rapidly as a function of the time between array and circle. This is true up to 200 milliseconds for subject "V.V." and 270 milliseconds for the other two subjects, later presentations seeming to have no further effect. Performance when the circle follows by less than 100 milliseconds is very much like that obtained in the erasure experiment using a circle without a bar marker.

4.2 *Discussion*

Results of this experiment indicate that it takes a significant time for subjects to detect a marker and read the designated letter, the level of performance being a function of the time available for detection and reading. Maximum performance requires times of the order of 200 to 270 milliseconds. Thus, the decay curves from the first experiment incorporate two effects: (a) storage time and (b) readout time. As we shall see in the next section, it is possible by means of the readout time measurement to correct for the latter factor and solve for the storage time alone.

V. STORAGE TIME

We indicated in Section III that performance in the bar-marker experiment is probably the result of two different types of performance on the part of the subject. First, there is a nonselective readout, which is independent of appearance of the marker; second, there is a selective process, which occurs only after the marker appears, when the subject has been cued to direct his attention to the single desired letter. The nonselective process is indicated by the finding that the subject's performance does not fall to zero even when the bar marker appears at relatively long times (450 milliseconds) after appearance of the array, at times when, presumably, the short-term storage has already decayed. It was separated out and measured in the erasure experiment, in which it is apparent that, if the subject has not read the designated letter from his short-term storage before the circle appears, he cannot read it later because the letter is erased by the circle.

We have no direct measure of the selective readout component. The effect of this component can be derived from the original bar-marker curves by subtracting out the nonselective component from the whole. Fig. 9 shows the result obtained by subtracting percentages obtained in the erasure experiment from those obtained in the bar-marker experiment. The subtraction is not a simple algebraic one. It is clear that if the subject reads out the correct letter by chance before the marker appears, designation by the marker cannot improve his performance. It therefore seems reasonable to treat the probabilities of reading letters before and after appearance of the marker as independent.

Designating these probabilities as P_B and P_A respectively, the total probability of reading the letter is $P_T = P_B + (1 - P_B)P_A$. P_T is the per cent correct in the first experiment, P_B that in the erasing experiment and P_A, the per cent in Fig. 9, is calculated from $P_A = P_T - P_B/(1 -$

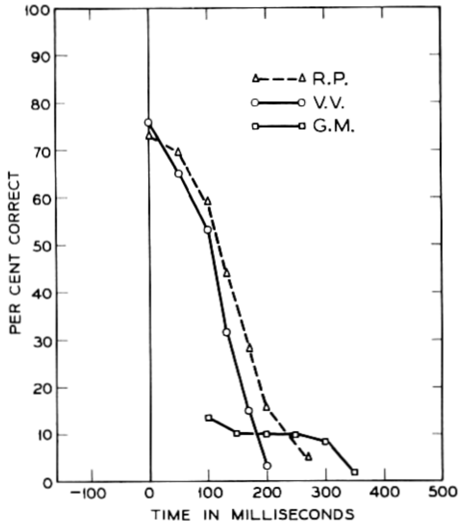

Fig. 9 — Derived "selective readout" performance curves.

P_B). The initial drop in the erasure curve is ignored because, as shown, it involves superposition and not simple erasure.

The derived curves for subjects "V.V." and "R.P." are quite similar. They start at their maxima and drop to zero as would be expected. That of subject "G.M." has the peculiar shape it does because the slope of his circle erasure curve between zero and 100 milliseconds is indeterminate. If this slope is estimated from the "filled circle" erasure curve, the the characteristic shown in Fig. 10 is obtained. This decay is quite similar to that of the other subjects.

Using these derived curves, it is possible to estimate the duration of the short term visual storage. Note that the curves in Figs. 9 and 10 represent that component of the subject's performance accomplished after appearance of the marker. We will assume that this component of performance is limited by the time available to detect the marker and read the letter before decay of the storage. We have already determined experimentally (see Fig. 8) the times required to detect a marker and read a letter to various levels of performance. By adding these readout times at each level of performance to the appropriate times in Figs. 9 and 10, estimates of the storage time are obtained. This process and the result are illustrated in Fig. 11.

The solid lines represent the selective readout components taken from Fig. 9 and, for subject "G.M.," from Fig. 10. The empty points were

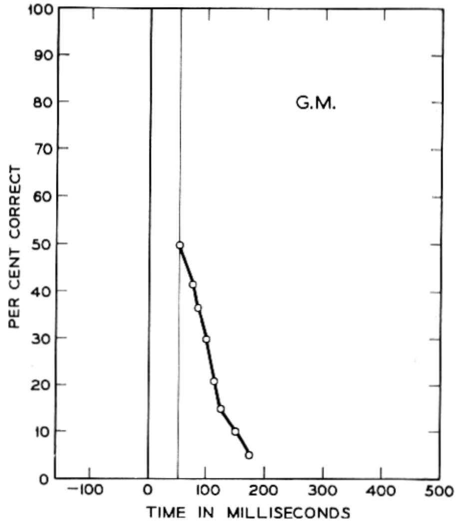

Fig. 10 — "Selective readout" performance curve for subject "G.M." derived from grid experiment.

obtained by adding times at various levels of performance taken from Fig. 8 to the points at the same levels of performance on the solid curve. Each point is therefore an independent estimate of storage time. It is seen that these points approximate vertical lines surprisingly well. The estimated storage times are 300 milliseconds. for "R.P." and 250 milliseconds for the other two subjects.

VI. CONCLUSIONS

In the light of the experiments reported here, the following interpretation seems plausible: The visual process involves a buffer storage whose read-in is very fast and readout relatively slow. The storage includes an erasure mechanism whereby new information put into the storage tends to erase what was previously there. This erasure is local in character, since erasure of a given detail depends on its distance from the areas where new detail is being put in. The storage time is of the order of one-quarter second. The storage capacity is more difficult to assess. A lower bound on the storage capacity, computed from performance obtained when bar marker follows immediately after array, yields a figure of 37 bits for the poorest subject and 54 bits for the other two subjects. This figure seems quite high, considering that the letter arrangement used in the experiment and the sharpness and contrast of the letters

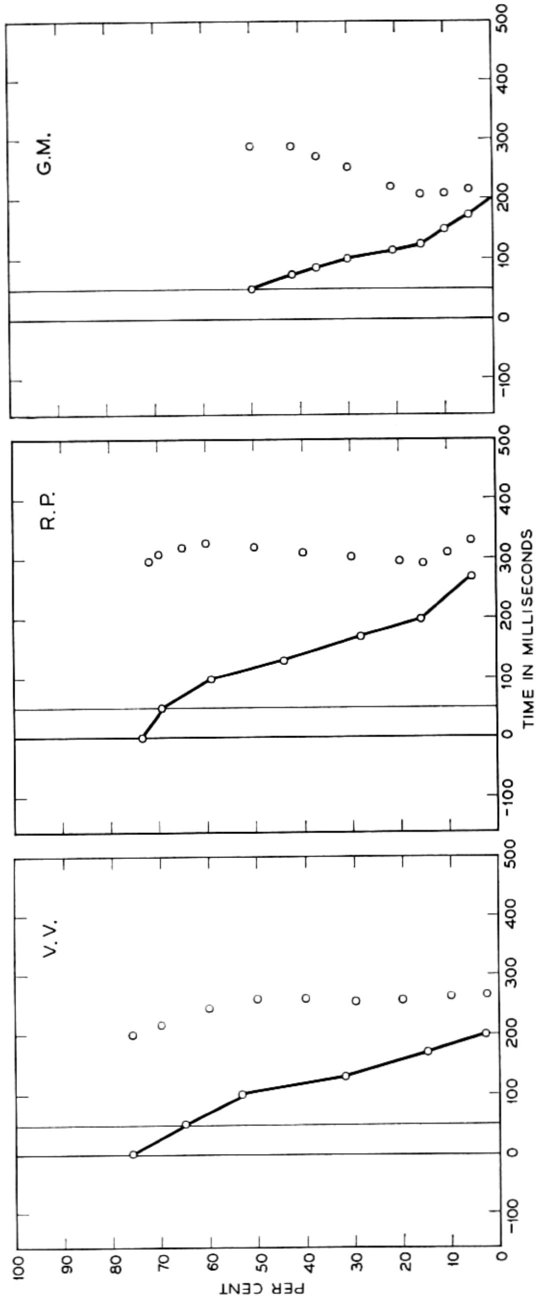

Fig. 11 — Derived storage time.

were not such as to maximize performance. The highest figure, obtained in span-of-perception experiments is 25.36 bits. Sperling,[7] using a technique similar to ours, also not involving complete report, obtained a value of 64 bits.

The interpretation above, of course, is a tentative one. These experiments have raised many more questions about short-term storage than they have answered. Particularly compelling are the questions of how the storage is scanned, and the stimulus factors involved in erasure. It is hoped that further application of the techniques used here will shed more light on these matters.

VII. ACKNOWLEDGMENT

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