Sensory Registration and Informational Persistence

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The traditional view of iconic memory as a precategorical, high-capacity, quickly decaying visible memory has recently come under attack (e.g., Coltheart, 1980). Specifically, distinctions have been drawn between visible persistence, or the phenomenal trace of an extinguished stimulus, and informational persistence, knowledge about the visual properties of the stimulus. In the present research we tested two alternative conceptions of informational persistence. One conception is that visual information persists in a visual memory that begins at stimulus offset and lasts for 150-300 ms. independently of exposure duration. The second is that informational persistence arises from a nonvisual memory that contains spatial coordinates for displayed items along with identity codes for those items. Three experiments were conducted in which 3×3 letter arrays were presented for durations ranging from 50 to 500 ms. A single character mask presented at varying intervals after array offset cued report of an entire row of the array. Comparison of the cued row's masked and unmasked letters revealed that spatially-specific visual (i.e., maskable) information persisted after stimulus offset, regardless of exposure duration. This result favors the visual conception of informational persistence. But there was also support for the nonvisual conception: Accuracy increased and item intrusion errors decreased as stimulus duration increased. The implications of these results for models of informational persistence and for transsaccadic integration during reading are discussed.

It has been known at least since Aristotle's time (384–322 B.C.) that visual sensation persists after stimulus offset (Allen, 1926). Contemporary interest in this property of the visual system was revived by Sperling (1960). In Sperling's experiments, subjects were presented an array of letters for some brief time. Following stimulus offset, a subset of the information in the array was cued for report. Sperling found that subjects' recall performance for the cued information was very high if the cue was presented within about 100 ms or so of stimulus offset. Furthermore, recall accuracy decreased as the time between stimulus offset and presentation of the recall cue increased. These results contrasted with performance when subjects were asked to report the entire array of letters. In this case, recall performance was limited to only a few items from the array. Taken together, these results suggested that immediately following stimulus offset there was more information available about the array than could be normally reported, but this information disappeared quickly with the passage of time. This persisting information appeared to be visual, because the visual characteristics of the exposure fields presented before and after the stimulus array had a sizable effect on recall accuracy. The method of sampling a subset of the total information in an array has been called *the partial report technique*, and the superior recall performance under these conditions *the partial report superiority effect*.

Other methods of investigating visual persistence were developed soon after. These methods attempted to measure directly the lingering, visible trace that remained after stimulus offset. Sperling (1967), for example, introduced a technique for measuring the phenomenal duration of a stimulus by adjusting the occurrence of a probe so that its onset and offset appear synchronous with stimulus onset and offset. Estimates of persistence duration obtained with this method approximated those obtained from partial report experiments (Haber & Standing, 1970). Eriksen and Collins (1967, 1968) used a technique in which two random dot patterns were presented sequentially in time, separated by an interstimulus interval. When superimposed, these patterns formed a nonsense syllable. Eriksen and Collins (1967) found that subjects could temporally integrate the two dot patterns to perceive the nonsense syllable over intervals as long as 100 ms, yielding an estimate of visible persistence duration approximating that obtained from partial report.

As a result of studies like these, almost all contemporary models of visual information processing now assume the existence of a very short-term visual memory, which stores the contents of a visual display for some period of time after its offset. Until quite recently, the characteristics of this memory (usually

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called "iconic memory" after Neisser, 1967) were thought to be well known; based on the results of hundreds of partial-report and "direct measurement" studies (see Coltheart, 1980, and Long, 1980, for reviews), the consensual view of iconic memory has been that it is a visible, precategorical, high-capacity, quickly decaying memory whose purpose is to register incoming visual information and hold it for further processing by other components of the information processing system (Coltheart, Lea, & Thompson, 1974; Dick, 1974; von Wright, 1972).

This view of iconic memory has been widely accepted and widely promulgated by memory researchers and textbook writers alike. Unfortunately, it is almost certainly wrong. A growing body of evidence now suggests that there is no unitary "iconic memory," but rather that there are several different kinds of visual memory early in the stream of information processing. The results of numerous studies indicate that the stimulus persistence measured by the partial report technique is identifiably different from that measured by the more direct techniques. For example, recent evidence suggests that partial report tasks and visible persistence tasks are differentially affected by stimulus factors such as intensity and duration: Visible persistence duration decreases with increases in stimulus duration and stimulus intensity (e.g., Bowen, Pola, & Matin, 1974; Di Lollo, 1977, 1980; Efron, 1970a, 1970b, 1970c; Haber & Standing, 1969, 1970), but duration and intensity have either no effect or a positive effect on partial report (Adelson & Jonides, 1980; Di Lollo, 1978; Loftus, 1985a; Long & Beaton, 1982; Sperling, 1960; Yeomans & Irwin, 1985). These differential effects imply different underlying memories.

Another problem for the traditional view of iconic memory is that the partial report technique, which has been so instrumental in the definition of iconic memory, appears to access more than just raw stimulus persistence. Several investigators have shown that most errors in partial report tasks are location errors rather than item intrusion errors (e.g., Dick, 1969; Townsend, 1973); that is, when subjects make an error, they tend to report some other letter that was present in the stimulus display, rather than a letter not contained in the display. Furthermore, familiarity with the stimulus array has been found to reduce the number of intrusion, but not location, errors (Mewhort, Campbell, Marchetti, & Campbell, 1981). These results suggest that the partial report procedure taps a postcategorical store in which items from the display are identified and remembered quite well, but their locations are forgotten.

This pattern of findings has led several investigators (e.g., Coltheart, 1980; Di Lollo, 1980; Mewhort et al., 1981) to challenge the traditional notion of iconic memory as a single, precategorical, visible memory. Coltheart, for example, has argued that there are at least three forms of visual persistence that follow stimulus offset: *neural* persistence, due to residual activity in the visual pathway; *visible* persistence, or the phenomenal impression that the stimulus is still visibly present; and *informational* persistence, which is what partial report measures, knowledge about the visual properties of the stimulus. Although the traditional view of iconic memory equates these three forms of persistence, Coltheart claims that visible persistence and informational persistence must be different from each other, because they are differentially affected by stimulus intensity and stimulus duration.

In Coltheart's estimation, visible persistence is merely a byproduct of neural persistence in the visual pathway. The source of informational persistence, however, is less clear. That is the focus of the present article-what is informational persistence, or in other terms, what does partial report measure? This is a question that has recently generated much interest (e.g., Coltheart, 1980, 1984; Di Lollo, 1978; Long, 1980; Mewhort et al., 1981; Mewhort, Marchetti, Gurnsey, & Campbell, 1984; Van der Heijden, 1981, 1984; Yeomans & Irwin, 1985), but few conclusions. In the research described below, we contrasted two major alternative conceptions of informational persistence. One conception, suggested by Yeomans and Irwin (1985), is that information persists in a visual memory that begins at stimulus offset and lasts for 150-300 ms, independently of exposure duration. This memory might consist of a visual analog of the stimulus display. Drift of the elements in the analog representation, in conjunction with passive decay, might produce the pattern of location and identity errors found by previous investigators. This "visual" conception of informational persistence is based on Yeomans and Irwin's (1985) demonstration that partial report performance is largely independent of exposure duration, and on previous research showing that the visual characteristics of pre- and postexposure fields have a large effect on partial report performance (e.g., Averbach & Coriell, 1961; Sperling, 1960). This conception of informational persistence is essentially a revised and extended version of the traditional view of "iconic memory." It differs from the traditional view in three ways: First, persistence is deemed to be "visual" (in the sense that it maintains shape and position information about display elements in a maskable form), but not necessarily "visible" (i.e., phenomenologically apparent); second, information in the visual analog is assumed to drift, as well as passively decay, as time passes after stimulus offset (this assumption is necessary in order to account for the preponderance of location errors over intrusion errors as cue delay lengthens); and finally, persistence is postulated to be independent of exposure duration (the traditional view has had little to say about exposure duration, because 50-ms exposures have been almost the rule).

In contrast, the second conception of informational persistence that we considered is one in which persistence arises from a nonvisual memory that contains spatial coordinates for items in the display along with abstract identity codes for those items. Both sources of information might decay rapidly in this memory, with faster decay for the spatial coordinates. Several models of this type have recently been proposed (e.g., Coltheart, 1980, 1984; Di Lollo, 1978, 1980; Mewhort et al., 1981, 1984); although these models differ in various ways, what they all share in common is the assumption that persisting information is recoded into a postcategorical, nonvisual format as time elapses from stimulus onset, and that it is this nonvisual information that is accessed by the partial report technique. The particular model of nonvisual informational persistence that we tested is that of Di Lollo, because it makes clear and specific predictions about subjects' performance in the experimental task that we employed. In Di Lollo's model, a visible, sensory recruiting phase that is activated by stimulus onset, sensitive to stimulus energy, and retinotopically organized is followed by a nonvisible interpretation phase during which display items are identified and categorized. During the recruiting phase, items from the display are "feature-encoded" and susceptible to erasure; during the interpretation phase, however, which begins approximately 100–150 ms after stimulus onset, items from the array are stored in a "meaning-encoded" form that is nonvisible and immune to erasure, with only poor coding of spatial information. Informational persistence corresponds to this latter phase of processing.

We contrasted these two alternative formulations of informational persistence by using a modified version of the Averbach and Coriell (1961) partial report procedure in which a circle cues report of an item from a letter array. Averbach and Coriell found that this cue caused masking at some interstimulus intervals. In the experiments described below, we examined the effect of stimulus duration on masking. On each experimental trial, subjects were presented a 3×3 letter array for some duration. Some period of time after array offset, a circle (actually a box in Experiment 2 and a noise mask in Experiment 3) was presented at one of the locations that had previously been occupied by a letter. This stimulus was a cue for subjects to report the entire row of the array in which the circle or mask appeared. Thus, data from both circled and uncircled (or masked and unmasked) locations were collected on a trial-by-trial basis. This aspect of the procedure makes it possible to assess whether visual (i.e., maskable) information is present after stimulus offset and also whether the spatial layout of the display is preserved.

Averbach and Coriell found that the circle cue produced strong masking effects on briefly presented (i.e., 50-ms) stimuli. The primary question of interest in the studies reported below is what effect increasing exposure duration will have on masking, because the visual and nonvisual formulations of informational persistence make different predictions: If informational persistence is due to a visual memory that begins at stimulus offset and lasts for 150-300 ms, independently of exposure duration, then significant amounts of masking should be found for all stimulus durations; that is, report of circled letters should be worse than report of uncircled letters for cue delays up to 150-300 ms, regardless of exposure duration. If, on the other hand, informational persistence reflects the translation of sensory information to abstract, nonvisual, identity codes with minimal representation of spatial position, as Di Lollo's model proposes, then masking should be found at short exposure durations, but not at longer ones. This is true because as time elapses from stimulus onset, more items from the display should become "meaning-encoded," spatial information should be lost, and the circle or mask should not necessarily line up with the letter that had occupied the masked position in the array.

Experiment 1

In Experiment 1, stimulus durations of 50 ms and 200 ms were employed. According to Di Lollo's model, 50 ms corresponds to a time when the recruiting phase should still be active, and 200 ms to a time when it should be complete. Thus, if Di Lollo's model is correct, the circle cue should cause masking for 50-ms exposure stimuli, but not for 200-ms exposure stimuli. The visual formulation of informational persistence, on the other hand, predicts that there should be masking for both exposure durations.

Method

Subjects. Six Cornell University undergraduates were used as subjects. All had normal or corrected-to-normal vision. Each was paid \$3 for each of two 1-hr sessions.

Apparatus. A two-field Harvard tachistoscope (Model T-2B-1) was used to present the stimuli and partial report cues. The stimuli consisted of one hundred 3×3 letter arrays printed on $4^{"} \times 6^{"}$ white matte cards. A Hewlett-Packard graphics plotter was used to make the stimuli. The letters were constructed from the duplex type-font. All letters were used except for vowels and the letter v. Each letter array subtended 3.6° of visual angle vertically and 3.35° horizontally when presented. Each letter was 0.62° high and 0.43° wide. Horizontal spacing between letters was 1.03°, and the vertical spacing was 0.87°. Nine partial report cue cards were also constructed. Each card contained a circle that aligned with one of the nine letter locations on the letter cards. These circles subtended 1.35° of visual angle in diameter. Thus, there was a 0.365° separation between the circle and the cued letter in the vertical direction, and a 0.46° separation between the circle and the cued letter in the horizontal direction. The stimuli and partial report cues were presented at a luminance of 16 fL (54.72 cd/m²). The experimental area was kept dark throughout the experiment, except for a small desk lamp, which allowed the experimenter to enter the cards into the tachistoscope and to record the subjects' responses.

Procedure. On each experimental trial a 3×3 letter array was presented for some duration, then some time after display offset the circle cue was presented to indicate which row should be reported. Subjects were instructed to report the three letters in the indicated row in their proper spatial order, guessing if unsure. Response omissions were not allowed. The experimenter recorded the subject's response on each trial. Subjects initiated each trial by pressing a triggering lever after the experimenter indicated that the cards were in place.

Two exposure durations (50 and 200 ms) and five cue delays (0, 50, 150, 300, and 500 ms) were employed in a completely crossed design. The pre- and postexposure fields consisted of a dark field. The circle cue was presented for 50 ms. In each experimental condition, the circle cue was presented equally often in each of the three rows, and randomly across all nine letter locations.

The experiment consisted of 10 blocks of 30 trials each. Each block contained only a single duration-delay pairing. The first five trials of each block were discarded as practice. Five blocks were run during each of two 1-hr sessions. The order in which the 10 duration-delay pairings were presented was randomized for each subject.

Results and Discussion

On each trial subjects made three responses, corresponding to the three letters they thought had been presented in the cued row. Each of these responses was scored as either a correct report (if the correct letter was reported in the correct position), a location error (if a letter from the 3×3 stimulus display was reported, but in the incorrect position), or an intrusion error (if a letter not contained in the 3×3 stimulus display was reported). Although this classification of the responses is straightforward, Mewhort et al. (1981) have pointed out that interpretation of their underlying causes is not; correct reports are a fairly unambiguous indicator of accuracy, and intrusion errors of misidentification, but location errors may be due to either localization failure or misidentification. Thus, intrusion and location errors are only imperfect indicators of misidentifications



Figure 1. Experiment 1: Correct reports, location errors, and intrusion errors for circled and uncircled letters as a function of cue delay for 50-ms exposures.

and mislocalizations; in particular, mislocalizations may be overestimated, and misidentifications underestimated, by this scoring procedure.

Figures 1 and 2 show the proportions of correct reports, location errors, and intrusion errors for this experiment, separately for circled and uncircled letters. Figure 1 contains the results for the 50-ms duration stimuli, and Figure 2 the results for the 200-ms duration stimuli. Both figures show the results for circled and uncircled letters as a function of cue delay. Separate analyses of variance were performed for correct reports, location errors, and intrusion errors, with factors of letter condition (circled vs. uncircled), stimulus duration (50 vs. 200 ms), and cue delay (0, 50, 150, 300, 500 ms). It should be noted that although separate analyses were conducted, the three response classes are not strictly independent, because together they sum to 100% of the responses; thus, the total number of errors will increase as accuracy decreases, and vice versa. But the breakdown of total errors into location and intrusion errors is not determined, so meaningful interpretation is not impossible.

For correct reports, the main effect of letter condition was

significant, F(1, 5) = 8.9, p < .05. Uncircled letters were reported more accurately than were circled letters. The stimulus duration main effect was marginally significant, F(1, 5) = 5.6, p < .07; 200-ms duration stimuli were reported more accurately than were 50-ms duration stimuli. The interaction of letter condition and cue delay was highly significant, F(4, 20) = 4.9, p < 100.01. Planned comparisons revealed that uncircled letters were recalled better than circled letters only for cue delays of 0, 50, and 150 ms. (Differences were 14.4%, 14.5%, and 14.0%; the width of the 95% confidence interval around these differences was $\pm 5.9\%$. Hereafter, we will use the term confidence interval halfwidth to describe comparisons such as these; in this instance, the confidence interval halfwidth is 5.9%.) The cue delay main effect was not significant, F(4, 20) = 1.5, p > .2; nor were the Letter Condition × Stimulus Duration, F(1, 5) = 1.3, p > 1.3.3; Stimulus Duration \times Cue Delay, F(4, 20) = 0.4, p > .7; and Letter Condition × Stimulus Duration × Cue Delay interactions, F(4, 20) = 0.5, p > .7. In sum, analysis of the correct reports revealed that significant masking occurred for both 50and 200-ms exposures. Circled letters were reported signifi-



Figure 2. Experiment 1: Correct reports, location errors, and intrusion errors for circled and uncircled letters as a function of cue delay for 200-ms exposures.

cantly worse than their uncircled neighbors as long as 150 ms after stimulus offset, regardless of exposure duration.

Location and intrusion errors were analyzed in order to investigate qualitative effects of masking on letter report. In the analysis of the intrusion errors, the main effect of letter condition was significant, F(1, 5) = 9.2, p < .03; and the main effect of cue delay, F(4, 20) = 2.8, p < .06, was marginally significant. There were more intrusions for circled letters than for uncircled letters, and more intrusions at longer cue delays. The interaction of letter condition with cue delay also approached significance, F(4, 20) = 2.00, p < .14. Planned comparisons of this interaction showed that there were significantly more intrusions for circled letters than for uncircled letters than for uncircled letters at cue delays of 0 (9.0%), 150 (6.6%), and 300 (5.6%) ms (95% confidence interval halfwidth = 4.4%). So, one effect of the circle mask was to produce a loss of identity information about the contents of the display.

In the analysis of the location errors, the main effect of letter condition was significant, F(1, 5) = 7.4, p < .05, as more location errors were made for circled letters than for uncircled letters. The interaction of letter condition with cue delay was also

significant, F(4, 20) = 4.3, p < .02. Planned comparisons showed that there were significantly more location errors for circled than for uncircled letters at cue delays of 50 (14.8%) and 150 (7.2%) ms, and marginally more at 0 (5.5%) ms (95% confidence interval halfwidth = 6.4%). Thus, another effect of the circle mask was to increase the number of location errors that were made for the masked item: Presentation of the circle mask within 150 ms of stimulus offset increased the report of other letters from the array at the circle letter's location.

The location errors were examined further in an effort to determine whether, when a location error occurred, letters in matrix locations spatially near the incorrectly reported location were chosen more often than letters in more distant locations. This is of interest in determining whether precise spatial information is maintained after stimulus offset; regardless of whether location errors arise from localization failure or misidentification, incorrect report of a letter spatially near the correct letter would indicate that spatial information had been preserved. Table 1 illustrates the distribution of correct reports and location errors for each position in the letter array, averaged over

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Experiment 1: Percent Correct Report and Distribution of
Location Errors (in %) for Each Array Position

Condition and row	Colu	mı	n 1	 Column 2		Column 3			
Circled letters									
Row 1	52	3	2	2	34	5	0	4	37
	6	3	2	6	14	4	4	6	12
	5	1	1	3	6	3	Ó	3	6
Row 2	2	0	0	2	4	1	0	5	5
	78	3	0	3	64	1	1	3	55
	3	3	0	2	8	2	2	5	10
Row 3	5	1	1	1	2	4	2	3	6
	5	5	0	4	7	8	1	4	8
	53	1	0	6	42	4	1	4	36
Uncircled letters									
Row 1	7 3	2	1	2	43	4	0	2	38
	4	1	0	2	11	3	1	3	17
	1	ō	Õ	2	6	3	2	1	10
Row 2	4	1	0	2	4	0	0	1	5
	79	0	0	3	69	2	0	1	63
	4	ŏ	Ŏ	1	5	Ō	2	Ō	9
Row 3	1	1	1	0	4	1	1	2	4
	4	2	1	4	11	3	2	3	11
	69	1	1	2	50	4	1	2	51

Note. This table shows a 3×3 response matrix for each position in the stimulus array, for both masked and unmasked letters. The italicized number in each response matrix indicates percent correct report for the indicated position in the array. The other numbers in each matrix indicate the proportion of responses in which a letter from another position was reported instead of the correct letter.

subjects, stimulus duration, and cue delay. In this table, a 3×3 response matrix for each array position is shown, for both circled and uncircled conditions. The italicized number in each 3×3 response matrix indicates percent correct report for that position in the letter array. The other numbers in each matrix indicate the proportion of responses in which a letter from another position was reported instead of the correct letter. So, for example, the first response matrix in Table 1 shows that when Position 1 was circled, the letter at that position was correctly reported 52% of the time; on 3% of these trials the letter next to it (in Position 2) was reported as having occurred at Position 1; on 6% the letter below it (in Position 4) was reported as having been presented at Position 1, and so on. The last response matrix, in the bottom right of the table, shows that when the letter in Position 9 was cued for report by the presence of a circle in Positions 7 or 8, the letter in Position 9 was correctly reported 51% of the time, and on 11% of these trials the letter just above it in Position 6 was incorrectly reported as having been presented at Position 9. Inspection of Table 1 suggests that when a location error occurred, a letter spatially near the correct letter was reported more often than a letter from a more distant location.

In order to quantitatively evaluate this pattern, two additional analyses were performed. For each location error, the Euclidean distance between the matrix location of the incorrectly reported letter and the matrix location of the letter that should

have been reported was calculated. So, for example, if Position 1 (top left) was cued for report but the subject responded with the letter that had been presented at Position 5 (in the center of the array), an error distance of 1.414 (the square root of the sum of the horizontal distance squared and the vertical distance squared) was recorded. Figure 3 shows the probability of incorrectly reporting a letter as a function of the letter's distance from the correct location under both circled and uncircled conditions. Also included in this graph is a line corresponding to a random distribution of location errors across all nine locations in the 3×3 stimulus display. This "random distribution" line was determined in the following way. For each array position in the matrix, there are eight other positions over which location errors may be distributed; over all nine array positions, then, there are 72 positions that correspond to location errors. Of these 72, 24 (33%) are of distance 1; 16 (22%) are of distance 1.414; 12 (17%) are of distance 2; 16 (22%) are of distance 2.24; and 4(6%) are of distance 2.83. These are the values plotted for the random distribution line in Figure 3.

An analysis of variance of the distance data in Figure 3 revealed that for both circled and uncircled letters there were significantly more errors of distance 1, and significantly fewer errors of distances 2, 2.24, and 2.83, than would be produced by a random distribution of location errors; there were also significantly fewer errors of distance 1.414 for the uncircled letters. These results indicate that when subjects made a location error, they reported a letter spatially near the correct letter rather than randomly choosing a letter from the array.

In the analysis reported above, location error distances were collapsed over stimulus duration and cue delay; in order to determine whether error distance changed as a function of these variables, an analysis of variance was performed on the distance



Figure 3. Experiment 1: Proportion of location errors that occurred at various Euclidean distances between the location of the correct letter and the erroneously reported letter. (The results for circled and uncircled letters are shown, along with the proportions expected by chance.)



Figure 4. Experiment 2: Correct reports, location errors, and intrusion errors for circled and uncircled letters as a function of cue delay, averaged over exposure duration.

data with factors of letter condition, stimulus duration, and cue delay. The visual formulation of informational persistence predicts that location error distance should increase as cue delay increases, due to drift of the array elements after stimulus offset. The nonvisual formulation of informational persistence predicts that location error distance should increase as exposure duration increases, because of increased meaning-encoding. In fact, only the main effect of letter condition was significant, F(1,5) = 8.44, p < .05. Location error distance for circled letters was slightly greater than for uncircled letters; as Figure 3 shows, there were more errors of distance 1 for uncircled than for circled letters, and more errors of distance 1.414 for circled than for uncircled. But location error distance was unaffected by stimulus duration and cue delay, varying nonmonotonically from 1.39 to 1.47 over cue delay and from 1.42 to 1.40 over exposure duration. In short, this analysis showed that when subjects made a location error, they tended to report a letter that was spatially close to the correct letter, and this tendency was unaffected by stimulus duration or cue delay. Because there was no effect of cue delay on error distance, it seems unlikely that significant drift of the array elements occurs after stimulus offset; rather, fairly precise spatial information is maintained.

To summarize the results of Experiment 1, significant masking was found up to 150 ms after stimulus offset, regardless of exposure duration. Furthermore, the spatial layout of the array was preserved after stimulus offset, as evidenced by the fact that erasure occurred only for the letter in the position where the circle cue appeared and that location errors were not randomly distributed over array positions. The presence of masking even after a 200-ms exposure during which items from the display should have been meaning-encoded and thus immune to erasure suggests that Di Lollo's formulation of informational persistence is incorrect; visual (i.e., maskable) information was present after stimulus offset even after a 200-ms stimulus presentation. This result favors a visual conception of informational persistence; but another assumption of the visual conception, that drift of the array elements occurs after stimulus offset, was not supported.

It is possible that Di Lollo's model is correct in principle, but with different timing parameters. That is, perhaps the recruiting stage takes longer than 200 ms to reach completion. If so, then masking might still occur, and spatial information might still be maintained, even after a 200-ms stimulus exposure, as Experiment 1 demonstrated. In order to test this hypothesis, in Experiment 2 exposure duration was varied from 50 to 500 ms to examine the effect of stimulus duration more fully.

Experiment 2

Method

Subjects. The 2 authors and 3 Cornell University students participated in this experiment. All had normal or corrected-to-normal vision. None had participated in the first experiment.

Apparatus. Stimuli were presented on a Tektronix 5103N oscilloscope equipped with P31 phosphor. A Digital Equipment Corporation PDP-11/24 computer controlled stimulus presentation via digital-toanalog converters. As in Experiment 1, the stimuli consisted of 3×3 letter arrays constructed from the set of all consonants excluding y. A square box, 1.3° on a side, was used instead of a circle to cue report because it was easier to plot on the oscilloscope. For consistency of reference, however, it will be called a circle. All other visual angles were identical to those used in Experiment 1. The experimental chamber was illuminated in order to prevent subjects from detecting phosphor decay.

Procedure. On each trial, subjects were presented a 3×3 letter array for either 50, 200, 300, 400, or 500 ms. After the array was extinguished, an interval of 0, 50, 150, 300, or 500 ms elapsed before the circle cue was presented. The subjects then typed their responses into the computer. Subjects initiated each trial by pressing the return key on the keyboard.

The experiment consisted of 20 blocks of 45 trials each. Exposure duration and cue delay were varied from trial to trial. Subjects completed the 20 blocks of trials in four 45-min sessions. Each subject contributed data for 36 circled letters and 72 uncircled letters per condition. Each of the nine display locations was circled equally often in each condition.

Results and Discussion

Subjects' responses were scored as in Experiment 1. Figure 4 shows the results (correct reports, location errors, and intrusion errors) for this experiment, averaged over exposure duration. The data for circled and uncircled letters for each exposure duration and cue delay are shown in Tables 2–4. Analyses of variance were performed for correct report and error measures, with factors of letter condition (circled vs. uncircled), stimulus duration (50, 200, 300, 400, 500 ms), and cue delay (0, 50, 150, 300, 500 ms).

In the correct reports analysis, the main effects of letter condition, F(1, 4) = 58.6, p < .002; stimulus duration, F(4, 16) = 23.0, p < .001; and cue delay, F(4, 16) = 22.6, p < .001, were all significant. Uncircled letters were reported more accurately than were circled letters, accuracy improved as exposure duration increased, and accuracy decreased as cue delay increased. The Letter Condition × Stimulus Duration, F(4, 16) = 3.7, p < .03; Letter Condition × Cue Delay, F(4, 16) = 22.8, p < .001; Stimulus Duration × Cue Delay, F(16, 64) = 1.8, p < .05; and Letter Condition × Stimulus Duration × Cue Delay interactions, F(16, 64) = 1.8, p < .05, were also all significant. Planned comparisons of this last interaction revealed that for stimulus durations of 200, 300, and 500 ms, uncircled letters were reported significantly more accurately than were circled letters for cue delays of 0, 50, and 150 ms; for stimulus durations of 50

Table 2

Percent Correct Reports for Circled and Uncircled Letters
as a Function of Stimulus Duration (in ms)
and Cue Delay (in ms) in Experiment 2

	Cue delay								
& letter condition	0	50	150	300	500				
50									
Uncircled	77.2	63.1	56.7	51.1	54.4				
Circled	48.3	34.4	49.5	44.5	46.7				
200									
Uncircled	73.3	73.3	68.3	65.0	52.8				
Circled	51.1	47.2	51.1	55.6	48.9				
300									
Uncircled	78.0	75.8	72,2	67.5	54.4				
Circled	55.6	57.8	48.3	64.4	52.8				
400									
Uncircled	80.0	76.4	70.8	61.1	59.7				
Circled	63.3	61.7	61.1	55.0	61.7				
500									
Uncircled	78.0	73.6	66.4	62.2	60.8				
Circled	59.5	60.0	55.0	65.6	60.6				

and 400 ms, uncircled letters were reported significantly more accurately than circled letters for cue delays of 0 and 50 ms, and marginally more accurately for cue delays of 150 ms (Bonferroni 95% confidence interval halfwidth = 10.6%). In essence, significant masking was found up to 150 ms after stimulus offset, regardless of exposure duration.

In the analysis of intrusion errors, the main effects of letter condition, F(1, 4) = 63.8, p < .002; and stimulus duration, F(4, 4) = 63.8, p < .002; and stimulus duration, F(4, 4) = 63.8, p < .002; and stimulus duration, F(4, 4) = 63.8, p < .002; and stimulus duration, F(4, 4) = 63.8, p < .002; and stimulus duration, F(4, 4) = 63.8, p < .002; and stimulus duration, F(4, 4) = 63.8, p < .002; and stimulus duration, F(4, 4) = 63.8, p < .002; and stimulus duration, F(4, 4) = 63.8, p < .002; and stimulus duration, F(4, 4) = 63.8, p < .002; and stimulus duration, F(4, 4) = 63.8, p < .002; and stimulus duration, F(4, 4) = 63.8, p < .002; and stimulus duration, F(4, 4) = 63.8, p < .002; and stimulus duration, F(4, 4) = 63.8, p < .002; and stimulus duration, F(4, 4) = 63.8, p < .002; and 16 = 43.8, p < .001, were significant, but cue delay was not, F(4, 16) = 2.2, p > .10. There were more intrusions for circled than for uncircled letters, and more intrusions for 50- and 200ms exposures than for 300-, 400-, or 500-ms exposures. The Letter Condition \times Cue Delay interaction was significant, F(4, 16) = 3.6, p < .03; there were more intrusions for circled than for uncircled letters only at cue delays of 0, 50, and 150 ms, and not at 300 or 500 ms (Bonferroni 95% confidence interval halfwidth = 5.0%). The Stimulus Duration \times Cue Delay interaction was also significant, F(16, 64) = 2.1, p < .02, although no systematic differences were apparent. The interaction of letter condition and stimulus duration was marginally significant, F(4, 16) = 2.7, p < .07, as was the interaction of Letter Condition \times Stimulus Duration \times Cue Delay, F(16, 64) = 1.7, p <.07. These interactions approached significance because the masking effect decreased as stimulus duration increased, especially at short cue delays. That is, the circle mask caused a loss of identity information, but this loss was ameliorated by stimulus duration.

In the analysis of location errors, the main effects of letter condition, F(1, 4) = 21.8, p < .01; stimulus duration, F(4, 16) = 4.8, p < .01; and cue delay, F(4, 16) = 8.5, p < .001, were all significant. There were more location errors for circled than for uncircled letters, more for 50-ms exposures than for the other exposures, and location errors increased as cue delay increased. The Letter Condition \times Cue Delay interaction was also signifi-

Table 3

Percent Intrusion Errors for Circled and Uncircled Letters
as a Function of Stimulus Duration (in ms)
and Cue Delay (in ms) in Experiment 2

<i>.</i>	Cue delay								
& letter condition	0	50	150	300	500				
50									
Uncircled	9.4	15.0	17.8	16.7	16.4				
Circled	26.1	28.3	22.2	12.2	23.3				
200									
Uncircled	9.2	10.0	8.9	8.9	22.2				
Circled	18.9	23.9	20.0	21.7	24.4				
300									
Uncircled	6.7	6.7	13.1	10.8	16.9				
Circled	17.2	14.4	21.7	15.0	15.0				
400									
Uncircled	7.5	7.5	11.1	13.6	14.2				
Circled	13.9	9.4	16.1	14.4	19.4				
500									
Uncircled	9.2	7.8	8.9	12.8	11.9				
Circled	15.6	13.9	17.2	12.2	8.9				

cant, F(4, 16) = 6.0, p < .005. Planned comparisons indicated that there were significantly more location errors for circled than for uncircled letters at cue delays of 0, 50, and 150 ms, but not at 300 and 500 ms (Bonferroni 95% confidence interval halfwidth = 5.6%). The Stimulus Duration × Cue Delay interaction was also significant, F(16, 64) = 2.1, p < .03, but no systematic patterns were apparent. The three-way interaction of Letter Condition × Stimulus Duration × Cue Delay was not significant, F(16, 64) = 1.5, p > .10. As in Experiment 1, then, part of the masking effect was due to an increase in reporting other letters from the array at the circled location.

Distance analyses of the location errors were conducted as in Experiment 1. Table 5 shows the distribution of correct reports and location errors for each position in the letter array, averaged over subjects, stimulus duration, and cue delay; as in Experiment 1, most of the location errors appear to cluster around the position that should have been reported. Figure 5 shows the probability of incorrectly reporting a letter as a function of the letter's distance from the correct position for both circled and uncircled conditions, along with a line corresponding to a random distribution of location errors. An analysis of variance of these distance data revealed that for both circled and uncircled letters there were significantly more errors of distance 1, and significantly fewer errors of the other distances, than would be expected by chance. The effects of stimulus duration and cue delay were also examined in another analysis of variance; in this analysis, the effect of letter condition was significant, F(1, 3) =24.95, p < .02, and so was the interaction of stimulus duration and cue delay, F(16, 48) = 1.9, p < .05. Location error distance was slightly greater for circled than for uncircled letters; no systematic patterns were apparent in the significant interaction. So, as in Experiment 1, when subjects made a location error, they tended to report a letter that was spatially close to the correct letter, regardless of stimulus duration and cue delay.

There were, however, other aspects of the data that were quite consistent with Di Lollo's model. Specifically, stimulus duration did have an effect on performance in this task. Figure 6 illustrates the effect of increasing exposure duration on report of circled and uncircled letters during the masking period. That is, it shows the accuracy and error data for each exposure duration, averaged over the cue delays when masking occurred, 0-150 ms. For the uncircled letters, accuracy for 50-ms exposures was significantly lower than for the other exposure durations; location errors decreased slightly, but nonsignificantly, as exposure duration increased; and there were fewer intrusion errors for exposure durations of 300-500 ms than for 50 ms. The circled letters showed similar, but more pronounced, patterns. Fifty-ms exposures were recalled significantly less accurately than all others; 200-ms exposures were recalled significantly less accurately than 400- and 500-ms exposures; and 300-ms exposures were recalled significantly less accurately than 400-ms exposures. For the location errors, there was a small but nonsignificant decrease with increasing stimulus duration, whereas the intrusion errors did decrease significantly as exposure duration increased: There were significantly more intrusions for the 50-ms exposures than for the 300-500-ms exposures, and significantly more for 200-ms exposures than for 400- and 500-ms exposures (Bonferroni 95% confidence interval halfwidths for correct reports, location errors, and intrusion errors were 5.1%, 5.5%, 5.1%, respectively, for both uncircled and circled letters). This pattern of results-increasing accuracy and decreasing in-

Table 4

Percent Location Errors for Circled and Uncircled Letters as a Function of Stimulus Duration and Cue Delay in Experiment 2

Stimulus duration	Cue delay (ms)								
condition	0	50	150	300	500				
50									
Uncircled	13.3	21.9	25.6	32.2	29.2				
Circled	25.6	37.2	28.3	43.3	30.0				
200									
Uncircled	17.5	16.7	22.8	26.1	25.0				
Circled	30.0	28.9	28.9	22.8	26.7				
300									
Uncircled	15.3	17.5	14.7	21.7	28.6				
Circled	27.2	27.8	30.0	20.6	32.2				
400									
Uncircled	12.5	16.1	18.1	25.3	26.1				
Circled	22.8	28.9	22.8	30.6	18.9				
500									
Uncircled	12.8	18.6	24.7	25.0	27.2				
Circled	25.0	26.1	27.8	22.2	30.6				

 Table 5

 Experiment 2: Percent Correct Report and Distribution of

 Location Errors (in %) for Each Array Position

Condition & row	Col	um	n l	Co	Column 2			Column 3		
Circled letters										
Row 1	65	2	ł	2	36	3	()	1	37
	6	1	1	2	10	5	2	2	2	22
	3	1	3	2	4	2	•	ł	3	5
Row 2	3	0	0	0	5	0	()	1	8
	85	1	0	1	82	1	()	0	77
	2	0	0	0	2	0	()	1	5
Row 3	7	3	4	5	5	4	2	2	4	5
	11	4	3	4	12	3	4	ŀ	5	23
	32	3	2	2	26	3	1	l	4	26
Uncircled letters										
Row 1	78	0	0	1	47	4	()	2	51
	5	0	0	3	10	3	1		2	16
	2	0	0	2	4	2	1	l	2	5
Row 2	3	0	0	0	1	0	()	0	4
	87	0	0	0	89	0	()	0	84
	3	0	0	0	1	0	()	0	2
Row 3	6	2	1	2	3	3	()	1	7
	6	1	2	2	9	3	1	l	2	20
	57	2	2	3	40	4	I	l	2	42

Note. This table shows a 3×3 response matrix for each position in the stimulus array, for both masked and unmasked letters. The italicized number in each response matrix indicates percent correct report for the indicated position in the array. The other numbers in each matrix indicate the proportion of responses in which a letter from another position was reported instead of the correct letter.

trusion errors—with increasing stimulus duration is what one would expect to find if sensory information were being identified or meaning-encoded during the exposure period. This is particularly true for the circled letters, because the longer the display is available for meaning-encoding, the less likely it is that the circle mask will interrupt the identification process. In sum, the results of the second experiment suggest that elements of both the visual and nonvisual models under consideration may play a role in informational persistence.

Experiment 3

Following the lead of Averbach and Coriell (1961), in Experiments 1 and 2 we used a circle mask to cue row report. Although fairly large masking effects were found in these two experiments, the form of the masking function was quite different from that obtained by Averbach and Coriell. They obtained a U-shaped function in which the circle mask had its greatest effect at a cue delay of 100 ms, somewhat smaller effects at longer delays, and almost no effect when the cue appeared concurrently with display offset. We also found a slight, but nonsignificant, nonmonotonicity in our masking functions, but unlike Averbach and Coriell we found a large masking effect when the circle cue appeared concurrently with display offset. Although our masking results are different from those of Averbach and Coriell, they are very similar to those of other investigators who have employed a circle or ring to cue letter report (e.g., Di Lollo, 1978; Eriksen & Collins, 1964, 1965; Eriksen, Collins, & Greenspon, 1967; Schiller & Smith, 1965); Kahneman (1968) has suggested that target energy may determine the form of the masking function produced by a circle mask, with high energy needed to obtain the U-shaped function found by Averbach and Coriell.

Given these complications associated with circle masks, we decided to replicate our basic experiment with a different kind of masking stimulus, a noise mask. Averbach and Coriell (1961), among others, have found that a noise mask has its greatest effect at zero delay and reduced effects at longer delays. In Experiment 3 we examine the influence of stimulus duration on this form of masking; judging from the results of Experiment 2, which provided some support for both models of informational persistence described earlier, we expected a sizable masking effect for cue delays of 0-150 ms, regardless of exposure duration; accuracy during the masking period should improve as stimulus duration increases; and intrusion errors during the masking period should decrease as stimulus duration increases.

Method

Subjects. The 2 authors and 4 Michigan State University students participated in this experiment. All had normal or corrected-to-normal vision.

Apparatus. Stimuli were presented on a Hewlett-Packard 1340A display scope equipped with P31 phosphor. A Digital Equipment Corporation Micro-11/23+ computer controlled stimulus presentation via digital-to-analog converters. As in Experiments 1 and 2, the stimuli consisted of 3×3 letter arrays constructed from the set of all consonants excluding y. Each letter in the array subtended 0.36° horizontally and 0.5° vertically; the distance between letters was 1.1° horizontally and



Figure 5. Experiment 2: Proportion of location errors that occurred at various Euclidean distances between the location of the correct letter and the erroneously reported letter. (The results for circled and uncircled letters are shown, along with the proportions expected by chance.)

 0.9° vertically. The noise mask consisted of a dot matrix 0.36° wide and 0.5° high. The experimental chamber was illuminated in order to prevent subjects from detecting phosphor decay.

Procedure. On each trial, subjects were presented a 3×3 letter array for either 50, 275, or 500 ms. Stimuli exposed for 275 and 500 ms were presented at a lower intensity than were those exposed for 50 ms, so that all displays appeared the same brightness regardless of duration (cf. Di Lollo, 1979). After the array was extinguished, an interval of 0, 50, 150, 300, or 500 ms elapsed before the noise mask was presented for 50 ms at one of the letter locations. Subjects typed their responses into the computer, reporting the three letters in the indicated row in their proper spatial order, guessing if unsure. Subjects initiated each trial by pressing the return key on the keyboard.

The experiment consisted of four blocks of 135 trials each. Exposure duration and cue delay were varied from trial to trial. Subjects completed the four blocks of trials in two 45-min sessions. Each subject contributed data for 36 masked letters and 72 unmasked letters per condition. Each of the nine display locations was masked equally often in each condition.

Results and Discussion

Subjects' responses were scored as in Experiments 1 and 2. Figures 7–9 show the results (correct reports, intrusion errors,



Figure 6. Experiment 2: Effect of exposure duration on correct reports, location errors, and intrusion errors for circled and uncircled letters at cue delays 0-150 ms.

and location errors) for this experiment, averaged over exposure duration for the unmasked letters but separated by exposure duration for the masked letters; Tables 6–8 show the complete, unaveraged data. Analyses of variance were performed for correct report and error measures, with factors of letter condition (masked vs. unmasked), stimulus duration (50, 275, 500 ms), and cue delay (0, 50, 150, 300, 500 ms).

In the analysis of correct reports, the main effects of letter condition, F(1, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, p < .001; stimulus duration, F(2, 5) = 102.7, P = 102.7, P10) = 34.9, p < .001; and cue delay, F(4, 20) = 6.7, p < .002, were all significant, as were the interactions of Letter Condition \times Stimulus Duration, F(2, 10) = 51.9, p < .001; Letter Condition × Cue Delay, F(4, 20) = 36.2, p < .001; Stimulus Duration × Cue Delay, F(8, 40) = 6.3, p < .001; and Letter Condition \times Stimulus Duration \times Cue Delay, F(8, 40) = 8.9, p < .001. Unmasked letters were reported significantly more accurately than masked letters at cue delays of 0-300 ms for 50ms exposures, and at cue delays of 0-150 ms for 275- and 500ms exposures (Bonferroni 95% confidence interval halfwidth = 9.4%). This replicates the basic finding of Experiment 2 and indicates once again that visual information persists after stimulus offset, regardless of exposure duration. Furthermore, consistent with the nonvisual formulation of informational persistence, there was a slight but nonsignificant increase in correct report of unmasked letters with increasing exposure duration, and, as Figure 7 shows, a large and highly significant increase in correct report of masked letters with increasing exposure duration. The noise mask had its greatest effect at zero interstimulus interval, as expected from previous research, but its effectiveness was greatly reduced by increases in stimulus duration.

In the analysis of intrusion errors, the main effects of letter condition, F(1, 5) = 78.9, p < .001; and stimulus duration, F(2, -1)10) = 21.9, p < .001, were significant, but cue delay was not, F(4, 20) = 1.5, p > .2. There were more intrusions for masked than for unmasked letters, and more intrusions for 50-ms exposures than for 275- or 500-ms exposures. The interactions of Letter Condition \times Stimulus Duration, F(2, 10) = 9.3, p < .006; Letter Condition \times Cue Delay, F(4, 20) = 16.5, p < .001; Stimulus Duration × Cue Delay, F(8, 40) = 4.4, p < .001; and Letter Condition \times Stimulus Duration \times Cue Delay, F(8, 40) = 7.4, p < .001, were also significant. Planned comparisons of the triple interaction showed that for masked stimuli there were significantly more intrusions for 50-ms exposures than for 275- or 500-ms exposures at cue delays of 0-150 ms (Bonferroni 95% confidence interval halfwidth = 6.9%). The same pattern was apparent for the unmasked stimuli, but the differences were nonsignificant. Thus, as in Experiment 2, increasing exposure duration led to a decrease in intrusion errors.

In the analysis of location errors, the main effects of letter condition, F(1, 5) = 76.8, p < .001; stimulus duration, F(2, 10) = 33.3, p < .001; and cue delay, F(4, 20) = 6.3, p < .002, were significant, as were the interactions of Letter Condition × Stimulus Duration, F(2, 10) = 7.7, p < .01; Letter Condition × Cue Delay, F(4, 20) = 11.0, p < .001; and Letter Condition × Stimulus Duration × Cue Delay, F(8, 40) = 3.0, p < .01. Planned comparisons of the triple interaction showed that stimulus duration had no significant effect on unmasked letters, but did reliably influence report of the masked letters: There were more location errors for 50-ms exposures than for 500-ms ex-



Figure 7. Experiment 3: Correct reports for masked and unmasked letters as a function of cue delay, averaged over exposure duration for the unmasked letters but separated by exposure duration for the masked letters.

posures at cue delays of 0-300-ms, with 275-ms exposures inbetween (Bonferroni 95% confidence interval halfwidth = 7.3%). Thus, increasing stimulus duration appears to decrease location errors as well as intrusion errors for masked items. What is not immediately apparent, however, is whether increasing stimulus duration reduces mislocalizations or misidentifications that result in location errors. Given the spatial specificity of the masking stimulus, however, it seems unlikely that the high proportion of location errors for brief, masked stimuli is due to mislocalization; rather, it seems probable that the mask obliterates the memory representation of the masked stimulus, so a nearby letter is reported in its stead.

Distance analyses of the location errors revealed results similar to those of Experiments 1 and 2. Table 9 shows the distribution of correct reports and location errors for each position in the letter array, averaged over subjects, stimulus duration, and cue delay. Figure 10 shows the probability of incorrectly reporting a letter as a function of the letter's distance from the correct position for both circled and uncircled conditions, along with a line corresponding to a random distribution of location errors. An analysis of variance of these distance data revealed that for both masked and unmasked letters there were significantly more errors of distance 1, and significantly fewer errors of the other distances, than would be expected by chance. A separate analysis of variance examining the effects of stimulus duration and cue delay on error distance revealed no significant main effects or interactions; so, as in Experiments 1 and 2, when subjects made a location error, they tended to report a letter that was spatially near the correct letter, regardless of stimulus duration and cue delay.

In summary, the results of Experiment 3 replicated those of Experiments 1 and 2, using a noise mask rather than a circle mask to cue report. Maskable information persisted for about 150 ms after stimulus offset, regardless of exposure duration. Spatial information about the letter array was preserved during this period, as indicated by the fact that the mask interfered only with report of the letter sharing its spatial coordinates and by the fact that location errors clustered around the position that should have been reported. Stimulus duration had a large effect on performance, however: Correct report of masked items



Figure 8. Experiment 3: Intrusion errors for masked and unmasked letters as a function of cue delay, averaged over exposure duration for the unmasked letters but separated by exposure duration for the masked letters.

during the 0-150-ms masking interval increased as stimulus duration increased, and the proportions of location and intrusion errors decreased. This overall pattern of results provides some support for both the visual and nonvisual models of informational persistence under consideration.

General Discussion

The purpose of the present research was to determine the source of informational persistence; in particular, the experiments were designed to test between a visual conception of informational persistence, in which information about a stimulus display persists in a visual memory that begins at stimulus offset and lasts for 150–300 ms independently of exposure duration, and a nonvisual conception of informational persistence, in which informational persistence, in which information about a stimulus display is maintained in a nonvisual memory that contains spatial coordinates for items in the display along with abstract identity codes for those items. The primary results of these experiments were the following: (a) Visual (i.e., maskable) information persists for a constant pe-

riod after stimulus offset, regardless of exposure duration; (b) the spatial layout of the stimulus display is preserved during the persistence period, as shown by the spatial specificity of the masking stimulus and the distribution of location errors; and (c) accuracy increases and misidentifications decrease as exposure duration increases, especially for masked letters. The persistence of a visual representation after stimulus offset that maintains precise spatial information about a display irrespective of exposure duration is inconsistent with a nonvisual model of informational persistence such as Di Lollo's (1978, 1980). But a purely visual formulation of informational persistence is also unable to explain all the results of the present study; it can not be, for example, that the beneficial effects of increasing exposure duration are due simply to the formation of a more robust visual "afterimage" after stimulus offset, for several reasons. First, in Experiment 3 longer exposures improved performance even though target energy was equalized across stimulus duration. Second, longer exposures did not persist longer than shorter exposures, as would be expected with a stronger afterimage (e.g., Long & Beaton, 1982). Finally, the nonrandom dis-



Figure 9. Experiment 3: Location errors for masked and unmasked letters as a function of cue delay, averaged over exposure duration for the unmasked letters but separated by exposure duration for the masked letters.

tribution of location errors, and the decrease in intrusion errors with increasing exposure duration, are difficult to explain strictly in terms of a decaying afterimage. Rather, some nonvisual coding of identity and location also seems to occur. In sum, the best account of informational persistence appears to be one that includes elements of both the visual and nonvisual models that we have been considering.

Figure 11 shows a model that attempts such a melding. This model assumes that sensory information from a display (labeled the *sensory representation* in Figure 11) is ultimately translated into relatively durable item identity codes that have associated with them some abstract representation of spatial position (e.g., spatial coordinates). This information is transferred to shortterm memory for report. According to the model, the longer a display is presented, the more time the translation process has to complete its recoding. Once the display is terminated, however, the translation process has to rely on whatever stimulus persistence is available. In this model, stimulus persistence is present in the form of a visual analog of the stimulus display; the duration of this analog representation is sensitive to stimulus exposure conditions, such as the presence of masking stimuli, and it is assumed to decay with the passage of time, but it maintains form and location information about the display for some period of time after stimulus offset in order to allow the translation process to extract further information about the presented items. Translation consists of the nonselective conversion (cf. the "nonselective readout" of Averbach and Coriell) of sensory or analog information into abstract identity codes and spatial coordinates of the array elements prior to the onset of the partial-report cue, but once the cue is presented it is used to select which array elements are translated and transferred to shortterm memory.

The model accounts for the results of the present experiments in the following way. For unmasked letters, performance is based on the visual analog and the nonvisual identity code. Accuracy is high immediately after stimulus offset, because the visual analog maintains precise form and position information about the display. As cue delay lengthens, however, the visual analog decays, and report must rely on the nonvisual code. Spatial information is coded less accurately at this level, so correct

Table 6
Percent Correct Reports for Circled and Uncircled Letters
as a Function of Stimulus Duration (in ms)
and Cue Delay (in ms) in Experiment 3

Stimulus duration & letter condition	Cue delay								
	0	50	150	300	500				
50									
Uncircled	74.7	73.3	66.8	62.3	50.2				
Circled	16.3	34.8	50.8	51.8	51.2				
275									
Uncircled	80.5	74.3	75.2	62.5	59.2				
Circled	55.5	55.2	64.5	60.7	57.7				
500									
Uncircled	80.8	78.0	73.2	66.0	63.3				
Circled	58.0	67.2	65.3	61.3	58.3				

reports decrease and location errors increase. Increasing stimulus duration affects performance by allowing more nonselective translation of display items to occur before stimulus offset; thus, the overall level of accuracy is higher for longer stimuli, and the proportion of intrusions lower. For masked letters, performance is based only on the nonvisual identity code because the mask interferes with or obliterates the visual analog representation of the masked item. For short exposure durations, there are few correct reports and many misidentifications (in the guise of both intrusion and location errors) because the translation process has had insufficient time to encode many stimuli. As exposure duration increases, more translation occurs, accuracy improves, and misidentifications decrease. Because the mask interferes with or destroys the visual analog representation of the target, the model predicts that the cue-delay functions for masked targets should be relatively flat, because correct report relies on the masked item being translated into nonvisual identity form prior to mask onset. If the mask is powerful enough and exposure duration is short enough (as in the case of the noise mask and 50-ms exposures in Experiment 3), correct report of masked items may actually increase as cue delay increases, because of nonselective readout from the visual analog

Table 7

Percent Intrusion Errors for Circled and Uncircled Letters
as a Function of Stimulus Duration (in ms)
and Cue Delay (in ms) in Experiment 3

Stimulus duration & letter condition	Cue delay								
	0	50	150	300	500				
50									
Uncircled	10.3	10.8	13.0	14.3	19.7				
Circled	44.0	32.2	23.7	15.8	18.5				
275									
Uncircled	6.5	9.7	9.0	13.2	17.3				
Circled	19.8	18.0	16.2	11.7	17.2				
500									
Uncircled	6.7	8.3	7.8	13.7	14.3				
Circled	16.8	14.3	18.2	18.3	13.8				

Table 8	
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Percent Location Errors for Circled and Uncircled Letters as a Function of Stimulus Duration (in ms) and Cue Delay (in ms) in Experiment 3

Stimulus duration & letter condition	Cue delay							
	0	50	150	300	500			
50								
Uncircled	13.5	14.5	18.8	21.7	28.7			
Circled	38.5	31.3	24.0	30.8	29.3			
275								
Uncircled	11.7	14.5	14.3	23.0	22.3			
Circled	23.2	25.5	17.5	26.3	23.7			
500								
Uncircled	11.7	12.2	17.8	19.0	20.8			
Circled	23.5	17.2	15.2	18.8	26.5			

prior to mask onset. The model also predicts that location errors due to mislocalization should increase as cue delay increases, because decay of the visual analog forces localization to depend on the relatively poorer coding of spatial information that exists at the nonvisual level.

The model presented in Figure 11 is similar to several other models of informational persistence that have recently been proposed, but it is also different in several important respects.

Table 9

Experiment 3: Percent Correct Report and Distribution of Location Errors (in %) for Each Array Position

Condition & row	Column 1		Column 2			Column 3			
Circled letters									
Row 1	64	0	2	2	36	3	0	2	41
	4	Ť	ō	4	8	3	2	4	13
	2	i	ĩ	2	3	ĩ	2	2	4
Row 2	2	0	0	0	2	0	0	2	4
	78	0	0	1	81	0	0	0	67
	3	2	Ó	1	2	0	2	2	5
Row 3	3	3	1	3	4	6	2	3	5
	5	2	2	2	9	5	2	2	16
	49	2	1	3	31	2	0	1	35
Uncircled letters									
Row 1	79	2	0	1	61	3	1	2	50
	1	Ô	Ō	0	4	3	2	1	12
	0	Ö	Õ	1	2	1	1	1	4
Row 2	1	0	0	0	1	0	0	2	2
	89	Ō	Ō	Ó	89	Ô	Ó	Ó	77
	Ő	Õ	Õ	Ŏ	Ő	1	1	1	3
Row 3	2	0	2	1	2	2	1	1	5
	2	í	ō	ĩ	5	3	1	ī	13
	_ 69	1	ŏ	2	59	2	i	2	47

Note. This table shows a 3×3 response matrix for each position in the stimulus array, for both masked and unmasked letters. The italicized number in each response matrix indicates percent correct report for the indicated position in the array. The other numbers in each matrix indicate the proportion of responses in which a letter from another position was reported instead of the correct letter.



Figure 10. Experiment 3: Proportion of location errors that occurred at various Euclidean distances between the location of the correct letter and the erroneously reported letter. (The results for masked and unmasked letters are shown, along with the proportions expected by chance.)

It is superficially similar to Di Lollo's model of informational persistence in the sense that at one level of representation information is visual and sensitive to stimulus energy, and at a second level display items are identified and categorized. The difference is that in Di Lollo's model the first level of processing depends on stimulus onset, whereas in our model it doesn't begin until stimulus offset. This is an important difference, however, because it defines the existence or nonexistence of a duration-independent visual analog representation after stimulus offset. Our model is also quite similar to the dual-buffer model of Campbell and Mewhort (1980; Mewhort et al., 1981; and see also Coltheart, 1984, who has endorsed a conception of infor-

mational persistence almost identical to that of Campbell and Mewhort). According to this model, information from a letter display is first stored in a raw, precategorical form in a feature buffer; our model, in contrast, distinguishes between stimulusdriven sensory information (contained in the sensory representation) and sensory persistence (contained in the visual analog). According to the dual-buffer model, the raw information in the feature buffer is transformed by a character identification mechanism into an abstract, postcategorical representation that is stored in a character buffer, which also preserves the relative spatial positions of items in the display; these correspond closely to our translation process and nonvisual identity code. In the dual-buffer model, when a partial report cue is presented, an attentional mechanism selects items from the postcategorical character buffer for report. Our selection process is somewhat different; it directs the translation process in its identification of the contents of the precategorical visual analog, in addition to guiding the transfer of information to short-term memory for report. According to the dual-buffer model, intrusion errors occur mainly because of data corruption at the feature level, whereas location errors are due primarily to retrieval failure (due to rapid decay of location information) at the character-buffer level. Masking affects both buffers at short stimulus onset asynchronies (SOAs), producing both identification and localization failures; at long SOAs (greater than about 150 ms), however, mask presentation is assumed to produce only localization failures, by distorting spatial information in the character buffer. In our model, masking affects only the visual analog representation of the masked stimulus, and has no effect at the nonvisual level (this is true, anyway, for the "perceptual" masks that we used; "conceptual" masks [e.g., Intraub, 1984; Loftus & Ginn, 1984; Potter, 1976] might have different effects).

Several of our results appear problematical for the dualbuffer model. First, mask presentation caused identification errors at SOAs considerably longer than 150 ms. Second, mask presentation caused spatially-specific information loss, rather than a general loss of spatial information; if masking produces spatial uncertainty in the character buffer, as the dual-buffer model proposes, one would expect equally deleterious effects on all items in the buffer, rather than spatially-specific loss of just



Figure 11. A new model of informational persistence. (Sensory information from a display is translated into nonvisual item identity codes with abstract spatial coordinates. Following stimulus offset, a visual analog representation persists for 150-300 ms, regardless of exposure duration; the visual analog maintains form and location information about the display in order to allow the translation process to extract further information about the presented items. Information from the nonvisual level is transferred to short-term memory for report.)

the masked item. Finally, the dual-buffer model seems to predict that location errors should increase as exposure duration increases, because as more time elapses from stimulus onset, more information should reach the character buffer, where location information is assumed to decay rapidly; in our experiments, however, location errors remained constant or decreased as exposure duration increased. The model in Figure 11 is able to account for all these results by postulating that masking has its effect on a duration-independent visual analog representation of the display, rather than on a postcategorical buffer activated at stimulus onset, and by holding that selection can occur before, and not just after, stimulus identification.

In conclusion, the results of the present study indicate that informational persistence is due both to a visual analog representation that maintains form and location information about the contents of a display for 150-300 ms after stimulus offset, regardless of exposure duration, and to a nonvisual identity representation that also contains some relatively poor coding of spatial layout. Further tests of this model could involve the manipulation of factors that should affect only one or the other of these two hypothesized memory systems, in order to further elucidate their characteristics. Also of interest is the extension of the model to other stimulus domains, such as pictures. Loftus, Johnson, and Shimamura (1985) have recently reported results that are in some ways intriguingly like our own. They showed subjects pictures for various exposure durations and sometimes presented a mask at various intervals after picture offset. They then tested subjects' memories for these pictures. Loftus et al. found that a picture masked immediately at stimulus offset had to be presented for about 100 ms longer than an unmasked picture in order for subjects to attain the same level of memory performance. This was true regardless of exposure duration or stimulus luminance. These results suggest that unmasked pictures have a persistence that is "worth" an extra 100 ms of exposure duration, regardless of their actual physical duration. Loftus (1985b) has also reported that mask luminance has a large effect on memory performance in this task when the mask is presented immediately after picture offset, but luminance has no effect if mask presentation is delayed by 250 ms; this was true for both 20- and 270-ms exposures, suggesting the presence of a duration-independent visual persistence. Although Loftus prefers to explain these results in terms of visible persistence, substantial previous work by Di Lollo (1977, 1980) and others has indicated that visible persistence duration is inversely related to stimulus duration; it may instead be that what we have been calling informational persistence (especially the visual analog component) underlies performance in the Loftus task. In our view, informational persistence occurs at a different level of processing from visible persistence, so stimulus duration need not have the same effects on the two kinds of persistence.

One final question of interest concerns the role that informational persistence may play in perception. Haber (1983) has pointed out that the traditional conception of iconic memory, based on 50-ms exposures and deemed visible and precategorical, is of little apparent value to normal perception; he believes the same arguments apply to informational persistence (personal communication, December 16, 1985). Although we agree with Haber's arguments against the traditional view, we believe that informational persistence is quite different from "iconic memory;" it maintains, for a constant period of time, form, location, and identity information about a display even after exposure durations that last as long as typical eye fixations. Informational persistence is not a raw, frozen image of a display, as iconic memory has been portrayed, but rather a mixture of visual and postcategorical information that persists at various levels of the perceptual/cognitive system following presentation of a stimulus. As others have suggested (e.g., Coltheart, 1984, Mewhort et al., 1981), one possible use of this kind of persistence is in the integration of information from successive eye fixations, especially during reading. A memory that maintains identity codes for items in a fixation, along with information about their relative spatial positions, might serve to bridge the period of saccadic suppression that separates fixations. In fact, there is empirical evidence to support this conjecture; Rayner, McConkie, and Zola (1980) have provided evidence for just such a memory in reading. In their experiments, a word was presented in the visual periphery, and subjects were instructed to move their eyes to it. During the eye movement, this word was replaced by a word which subjects read. Rayner et al. found that the initially presented word facilitated naming of the second word when the two words shared the same beginning letters, regardless of their case. They concluded that some nonvisible letter identity code from the first word was stored and integrated with the word presented after the saccade. It is possible that the nonvisible letter identity code isolated by Rayner et al. is identical to the informational persistence found in partial report experiments. This potential relation is complicated, however, by the findings of McConkie, Zola, Blanchard, and Wolverton (1982), who failed to find evidence of visual integration across fixations when subjects read meaningful, connected text rather than words in isolation. Thus, the role of informational persistence in transsaccadic integration during reading remains an intriguingly open question.

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