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Memory

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Sensory and Perceptual Storage

Data and Theory

Dominic W. Massaro
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Like William James's opinion that everyone knows what attention is, we all think we know what sensory storage is. Pashler and Carrier's introductory chapter in this volume set the foundation for the prototypical information processing model. Preperceptual (what we also call sensory) storage is usually designated as the first box in the information processing chain. The decade and a half beginning about 1960 was concerned with the properties of this initial storage structure. A variety of paradigms were brought to bear on the issue and a reasonable convergence of opinion was established. Neisser (1967) and many others to follow envisioned an iconic store of around a quarter of a second and an echoic store of several seconds.

Notwithstanding our understanding, one limitation was that the theorists were not clear about what they meant by sensory storage. Neisser (1967), for example, envisioned auditory sensory store as functional for the foreigner who is told, "No, not zeal, seal." The listener would not profit from this feedback if the /z/ was not maintained long enough to compare it to the /s/. If this were what was meant by sensory memory, however, then we should not have been so concerned with its time course. We must have an auditory perceptual memory that allows us to recognize not only the difference between the recently spoken "zeal" and "seal," but also a spoken word we have not heard for years. In this review, we make a clear

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distinction between sensory storage and perceptual memory. Sensory storage is the initial maintenance of a stimulus event for immediate processing. Its duration sets the limit on how much time is available for processing. Perceptual memory is one of the outcomes of processing the sensory storage. Its life span is orders of magnitude longer than sensory storage.

In Section I in this chapter, we review the literature aimed at describing characteristics of initial visual storage and briefly sketch early conceptualizations of iconic memory. In Section II, we present an analogous treatment of initial auditory storage. In both domains, we use a semichronological organization to present findings from the three major tasks that have been used to study both visual and auditory sensory storage: partial report, backward masking, and subjective estimation of phenomenal presence. In Section III, we address how the early conceptions of the icon have changed over recent years in response to certain seemingly contradictory results about its nature and, in Section IV, we discuss a new linear-systems approach for thinking about iconic storage and visual information processing that reconciles these apparently contradictory results within a unitary framework. In Sections V and VI, we review the evidence for multiple types of perceptual memories as opposed to stores for more abstract or symbolic information and discuss the issue of how such perceptual memories or stores should be represented, if at all, within models of information processing.

I. VISUAL SENSORY STORE

It has been recognized for centuries that the perceptual experience of a briefly presented visual stimulus outlasts the stimulus itself. This phenomenon can easily be demonstrated in any perception laboratory; one need only present a visual stimulus very briefly (e.g., for 10 ms) and follow it by darkness. The resulting experience is that the stimulus fades away over a period of perhaps 300 ms. Indeed, naive observers believe it to be the physical stimulus that is fading, supposing perhaps that the bulb in the projecting device is extinguishing slowly rather than abruptly. Such an observer is surprised to learn that the fading is a mental rather than a physical event. Neisser's (1967) dubbing this visual sensory memory "iconic" was adopted by the field.

A. Visual Partial-Report Task

The first person to use this task was George Sperling in his seminal 1960 study. He realized that a whole report of a visual display of test characters was limited by the number of items that could be held in short-term memory (Miller, 1956). Bypassing this limitation using a partial report, Sperling

could study the extraction of information from the iconic image and its placement into short-term memory. In a typical partial-report experiment, the stimulus might consist of a 4 (columns) × 3 (rows) array of letters in which only a single row was to be reported. The to-be-reported row (top, middle, or bottom) would be signaled by a tone (high, medium, or low frequency) that occurred sometime following stimulus offset. Total available information was estimated by multiplying the number of reported letters per row by the number of rows in the stimulus array. Sperling found that much more information was being held in a sensory store that decayed rapidly after stimulus offset. Before this hypothesis could be accepted, however, Sperling and other investigators realized that both short-term memory and loss of location information had to be eliminated as possible influences on the results.

As with any task, no matter how simple, performance in the partial-report task is multiply determined. Specifically, a performance decrease with a cue-delay increase could be a simple function of loss of information from short-term memory (STM). Sperling (1960) recognized this possibility and tested it with a different kind of partial-report cue. Two rows of four items each were presented with two digits and two consonants randomly mixed in each row. In this case the high or low tone cue indicated which category (letter or digit) to report. Performance in this condition was no better than that occurring in a whole report. This experiment and many to follow indicated that a decrease in partial-report performance with increases in cue delay could be demonstrated when a loss of STM was not responsible for the results.

There is no doubt that performance decreases with increases in the delay between the test display and the partial-report cue. Traditionally, it was assumed that the decrease in performance reflected the time to encode the test items in the display. When the partial-report cue came early, there would be plenty of time to switch attention to the cued row and selectively process the appropriate items while they were still in the visual sensory store. With increases in the delay of the cue, subjects become limited to what would normally be given in a whole report. In this interpretation, it is the identity of the letters that is critical for performance.

Mewhort and colleagues (Mewhort, Campbell, Marchetti, & Campbell, 1981) on the other hand, argue that most of the subjects were making errors on the location of the critical letters, not on their identities. This interpretation assumes that the letters have been recognized and that the delay in the cue presentation leads to poorer performance because of the participant forgetting the location of the test letters. The important influences that have been uncovered between identity and location information and the relationship between the two were not in the literature at the time of Sperling's (1960) and related investigations. We now know that location and identity are processed by somewhat independent channels in the visual system, and these two dimensions must be integrated (Treisman, 1986; Treisman & Gelade, 1980). Certainly, accurate performance given a partial-report cue requires that both of these dimensions be accurate.

Lupker and Massaro's (1979) study, however, showed that resolving the identity of the test letter is a time-extended process, and the partial-report advantage cannot simply be due to a loss of short-term memory or location information. They presented a display of four items positioned on the corners of an imaginary square centered around a fixation point. A single target letter, chosen from the set E, I, F, and T, was presented. The other three characters in the display were either all zero or all a hybrid letter highly confusable with the target letters. The 10-ms display was preceded or followed by a cue indicating the position of the target letter. The cue was either an arrow pointing to the target or a pattern mask positioned at the same location as the target.

The arrow cue improved performance if it was presented within 200 ms of the display. As often noted, the advantage of performance in the cuing condition could simply be due to less forgetting from short-term memory. Similarly, the location-forgetting hypothesis would state that this advantage is due to the forgetting of location information with increases in arrow cue delay. Given these alternative hypotheses, performance with the pattern mask cue is central to the experiment.

If the decreased performance with increases in cue delay were simply due to a loss of short-term memory or location information, the pattern mask cue should be an equally effective cue. Given that the items would be in a symbolic form, performance should be better with a shorter interval between the test display and the cue. However, the pattern mask cue was found to disrupt performance rather than to improve performance. The pattern mask cue actually produced a masking function: performance improved with increases in cue delay. Thus, it is reasonable to conclude that letter identification is a time-extended process that can be facilitated by an arrow cue but interfered with by a pattern mask.

B. Visual Backward Recognition Masking

Loftus and Hogden (1988) studied visual backward recognition masking (VBRM) in a picture memory task. Subjects studied naturalistic, colored pictures presented for 40 ms each. The pictures were presented alone or followed by a noise mask after some blank interstimulus interval (ISI). The mask was a jumble of black lines on a white background. Perceptual performance was assessed by memory performance in a later recognition test. Performance improved with increases in the ISI out to about 300 ms at which time it reached the level of the no-mask condition. These results replicated the findings from a plethora of studies carried out with alphanumeric test items, and they showed an impressive correspondence between their estimate of visual sensory memory and the estimate reached in the partial-report tasks. Even more striking is the fact that the results from these VBRM studies are exactly analogous to those from studies investigating auditory information processing, as detailed in the next section.

C. Estimation of Visible Persistence

The second perceptual event around which the concept of iconic store was intimately entwined was phenomenological appearance. Aside from an observer's ability to extract information from a stimulus, the stimulus appears consciously present to one degree or another, and stimulus appearance, like available information, fades gradually following stimulus offset. The duration of phenomenological presence following stimulus offset can be measured in various ways: the most simple and direct is a synchrony-judgment procedure in which a stimulus is followed after some ISI by a salient signal such as an audible click. The ISI is under the control of the subject, whose task is to set the interval such that the stimulus seems to have phenomenologically disappeared at the exact instant that the click occurs. The magnitude of the ISI is then taken to be the iconic image's duration.

D. Early Conceptions of Iconic Memory

The general conception of iconic memory that emerged from these three types of studies is presented in Figure 1, which assumes a visual stimulus presented for a (somewhat arbitrary) duration of 40 ms, and depicts what is referred to as "magnitude of perceptual event" as a function of time since stimulus onset. As is evident, the putative "perceptual event"—the perceptual response that occurs as a result of the physical stimulus presentation—is conceptualized to begin at stimulus onset, to remain at some constant level during stimulus presence, and then to decay following stimulus offset. The usual assumption was that decay is exponential; accordingly, exponential decay is incorporated in Figure 1.

Implicit in the representation of Figure 1 is the idea that perception of a briefly presented stimulus invokes two sets of perceptual events. First, "normal" perception takes place "when it should," that is, while the stimulus is physically present. Second, perception also takes place during a brief period following stimulus offset, that is, during the iconic-decay period. Given this situation, a basic question addressed over the years is: Why did evolution provide this perceptual appendage; that is, why does perceptual activity continue past stimulus offset, and what role does such processing play in normal perceptual activity? A conclusion that we shall eventually reach in

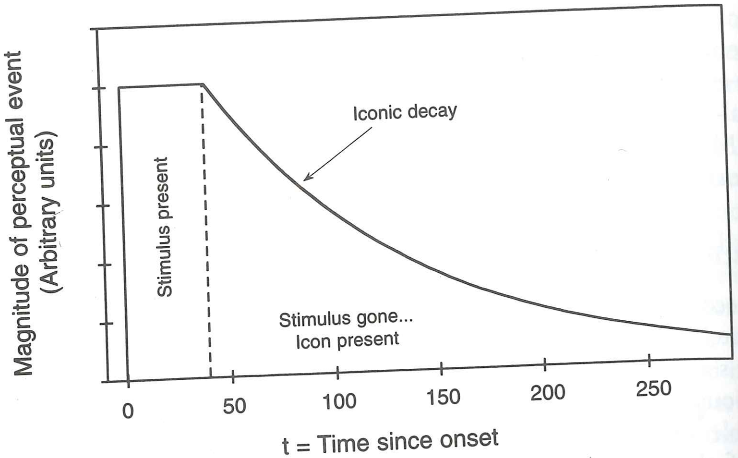

FIGURE 1 Assumed perceptual events surrounding a brief visual presentation.

this chapter is that this question is not a meaningful or interesting one. The ordinate of Figure 1, "magnitude of perceptual event," is deliberately vague, as it came to refer to two separate aspects of perception. When applied to information extraction, the "perceptual event" of Figure 1 would refer to "amount of information available to be extracted and placed into short-term store" (e.g., Averbach & Coriell, 1961; Sperling, 1960; see also Averbach & Sperling, 1961, who characterized available information as measured in bits). As indicated in Figure 1, all stimulus information was assumed to be available during stimulus presence, while available information decayed following stimulus offset. When applied to phenomenological appearance, the "perceptual event" of Figure 1 might be operationally defined as "apparent luminance" (e.g., Weichselgartner & Sperling, 1985), the implicit assumption being that a fading icon is literally equivalent to a physical stimulus fading in luminance. This early work resulted in a general conception of an iconic memory having the following characteristics.

1. Iconic memory constitutes the first mental representation of visually presented information.

2. Iconic memory is of large capacity (possibly including all information encodable by the initial stages of the visual system).

3. Iconic memory begins to decay immediately following stimulus offset, disappearing entirely after approximately 200–300 ms.

4. Information in iconic memory is such that it can be assessed by physical characteristics. Thus, for example, a subject engaged in a partial-report task can select letters from a letter array based on the physical characteristic

of letter position (e.g., report letters in the third row). Letters can also be reported based on other physical characteristics, such as color (e.g., report all the blue letters) or size (e.g., report all the large letters). However, a subject cannot select letters by characteristics based on meaning (e.g., a subject cannot select all the vowels in a letter array). In this sense, information in iconic memory was thought to be precategorical, that is, information that had not yet been pattern recognized and assigned meaning.

5. The iconic image can be destroyed if the stimulus is followed not by a blank field but by a visual mask of some sort.

6. Various techniques for measuring iconic memory's duration (e.g., partial report and synchrony judgment) were all thought to measuring the same entity; that is, decaying available information and decaying phenomenological appearance were thought to issue from the same, unitary, internal event.

II. AUDITORY SENSORY STORE

Like visual experience, some auditory experiences appear to outlast the sounds producing them. One argument for an auditory sensory store is based on the fact that sound is continuously changing. How could we recognize the informative segments of speech if the system did not hold on to the earlier part of a segment until the later part occurred? Research in the 1970s was directed at measuring the duration of this storage. We briefly review the same three tasks used in the study of iconic memory and the results from each task.

A. Auditory Backward Recognition Masking

One of the most successful tasks in studying audition has employed auditory backward recognition masking (ABRM). As stated earlier, Neisser and others had claimed that the auditory sensory storage lasted on the order of seconds. Some tension existed in the empirical trenches, however, as the result of work by Massaro (1970a, 1972), who extended the backward masking paradigm from the visual world and from auditory detection to study the time course of auditory recognition. In auditory backward recognition masking, a brief target stimulus is followed after a variable ISI by a second stimulus (the mask), and the amount of time that the target information is available in preperceptual memory can be carefully controlled by manipulating this duration. Using this procedure, Massaro found the accuracy of target identification to increase as the ISI increased out to about 250 ms (see also Cowan, 1984; Hawkins & Presson, 1986; Kallman & Massaro, 1979, 1983).

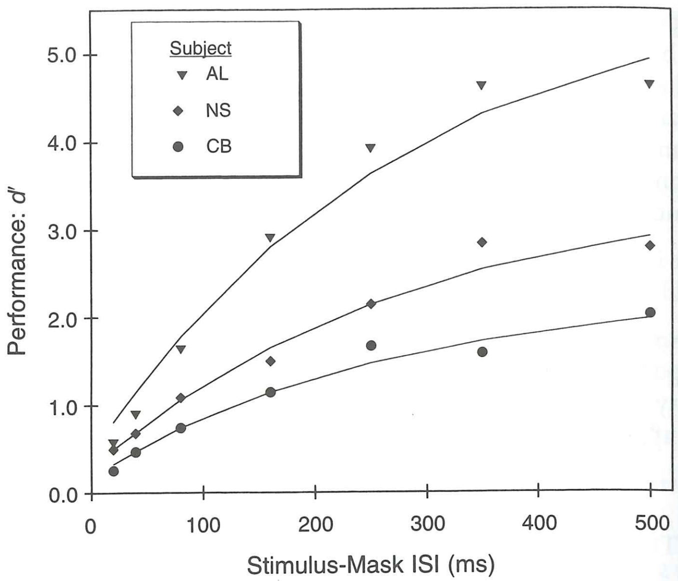

FIGURE 2 Identification of the test tone measured in d' units as a function of the silent interval between the test and masking tones. Results for three subjects. (Data from Massaro, 1970a.)

These backward masking results were explained within the framework of a model of auditory information processing in which the target sound is transduced by the listener's sensory system and stored in a preperceptual auditory store that briefly holds a single auditory event (Massaro, 1972, 1975a). Processing of the target sound is necessary for perceptual recognition. The mask replaces the target in the preperceptual auditory store and terminates any further reliable perceptual processing of the target, but it does not work retroactively. Masking does *not* reduce the amount of information that is obtained before the occurrence of the mask; it can only preclude further processing. Therefore, the terminology backward should be taken to mean only that the mask comes after the test stimulus.

In backward masking studies, performance typically asymptotes at an ISI of roughly 250 ms and this interval has been interpreted to reflect the duration of the preperceptual auditory store (Cowan, 1987; Kallman & Massaro, 1983). That is, the mask no longer affects performance after about 250 ms because the preperceptual trace is thought to no longer be available for processing. The three masking functions shown in Figure 2 represent the performance of three different young adults in an early study of auditory backward recognition masking (Massaro, 1970a). The two test alternatives were brief tones (20 ms) differing in frequency (770 and 870 Hz), the mask was another tone (820 Hz), and the subjects identified the test tone as high or low in pitch. Although there are individual differences in Figure 2, all three subjects asymptote at roughly the same interval of 250 ms.

Performance is measured in d' values rather than percentage correct because d' values have been shown to be less contaminated by decision biases in this task (Massaro, 1989). Larger d' values signify better discrimination between the two test tones, and the masking function shows the changes in this discrimination. The functions in Figure 2 can be described accurately by a negatively accelerated exponential growth function of processing time,

$$d' = \alpha(1 - e^{-\theta t}), \quad (1)$$

where the parameter α is the asymptote of the function and θ is the rate of growth to the asymptote. This function can be conceptualized as representing a process that resolves some fixed proportion of the potential information that remains to be resolved per unit of time. Thus, the same increase in processing time gives a larger absolute improvement in performance early relative to late in the processing interval. Zwislocki (1969) has offered a similar account (see Cowan, 1984, 1987).

Similar masking functions have been observed for a variety of auditory perceptual properties, including loudness, timbre, duration, and location, as well as speech distinctions (Massaro, 1975b; Massaro, Cohen, & Idson, 1976; Massaro & Idson, 1978; Moore & Massaro, 1973). In an unpublished study, subjects identified three properties of 20-ms test tones: pitch, loudness, and location (ear of presentation). The test tone could be followed by a masking tone after a variable ISI or no mask would be presented. For each property, the difference between the two alternatives was adjusted to give an average performance of 75% correct. The identification of all three properties showed the prototypical masking results. Performance improved with increases in ISI, reaching an asymptote at about 250 ms. Thus, these results provide additional evidence for an auditory sensory store of about 250 ms.

B. Detection versus Recognition

It should be noted that detection of the presence of an auditory signal versus recognition of the signal are not equally susceptible to backward masking. As shown by Bland and Perrott (1978), who contrasted detection and recognition masking, detection of presence versus absence can occur much more quickly and becomes immune from backward masking after only a few tens of milliseconds. In their detection task, a 10-ms pure tone was randomly presented on half of the trials, and nothing was presented on the other half. The subjects indicated whether or not a test tone had been presented. In the recognition task, a high or low test tone was presented on every trial. The subject's task was to identify the tone as high or low. In both tasks, the

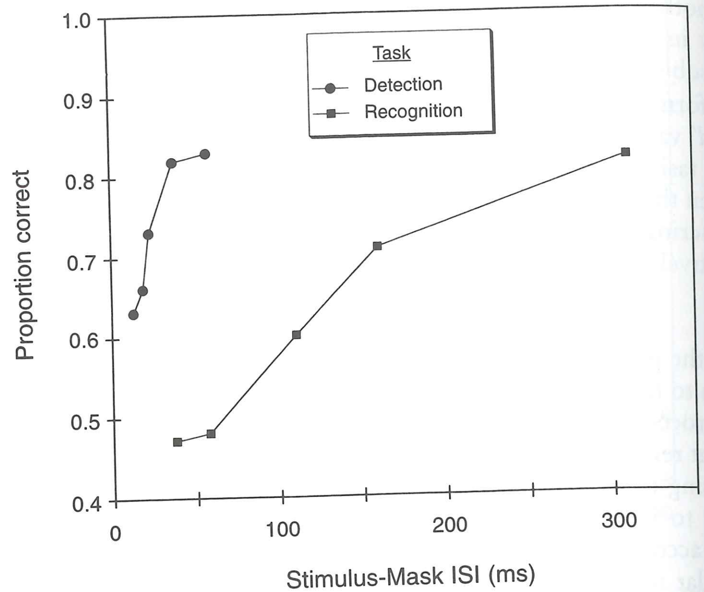

FIGURE 3 Percentage correct detection and recognition performance as a function of the silent interval between the test and masking tones. (Data from Bland & Perrott, 1978.)

observation interval was always followed by a 150-ms masking tone after a variable silent interval. Given two alternatives on both tasks, accuracy of performance can vary between 50 and 100%. As can be seen in Figure 3, detection and recognition were found to follow two different time courses. Detection performance reached asymptote (the highest level of performance) at around 50 ms, whereas recognition did not reach this level until there was at least three times as much silence between the test and target tones.

A similar distinction between detection and recognition exists in visual information processing. Breitmeyer (1984), summarizing the field of visual masking, provided evidence for different masking functions in detection and recognition. Detection is primarily a function of peripheral, energy-dependent, sensory integration and does not improve beyond a target mask asynchrony of about 100 ms. Recognition masking functions extend to longer intervals on the order of 200–250 ms and are influenced by more cognitive variables such as the allocation of central attention to the test items.

The masking results demonstrate the difference between detection and recognition. Detection of a change is sufficient for detection, whereas recognition of a pattern is necessary for recognition. Our perceptual world is rich, not because we detect change, but because we recognize patterns. The storage structures of echoic and iconic memory allow this recognition process to take place.

C. Auditory Partial-Report Task

The Bland and Perrott (1978) study and numerous other studies of auditory backward recognition masking have estimated the duration of echoic memory at around 250 ms. This number, however, conflicts with estimates from other paradigms, notably the partial-report and the suffix tasks. Perhaps the most famous partial-report task was carried out by Darwin, Turvey, and Crowder (1972), from which they estimated echoic memory to be on the order of about two seconds. Three lists of three items each were presented to the left, middle, and right of the subject's head, and following Sperling's procedure, subjects were cued to report the items in terms of either spatial location or category name (digits or letters). For some reason, however, spatial location information had to be reported as well in the category recall condition. The observed advantage of location recall over category recall, therefore, could have been due to this confounding and thus not indicate anything about the availability of information in echoic memory. (This single collaboration among these three superb researchers might have been unfortunate for the field. Each of the three seemed to have dissociated himself from the research almost immediately thereafter, but their erroneous conclusion has found its way into almost every introductory textbook in cognitive psychology; Greene, 1992, p. 11, is a recent example.)

Darwin et al. (1972) also found that partial report by spatial location was superior to whole report and decreased with increases in delay of the partial-report cue. However, the difference between the partial-report condition and the whole-report condition was embarrassingly small. Measuring performance in terms of items, the difference was actually less than half an item. For partial report, in terms of the number of items available, there were 4.9 items with an immediate cue and 4.4 with a 4-s cue delay. The whole report was 4.3 items correct. This small difference between the partial and whole report could easily have come from another process than sensory storage, most notably short-term memory. With a presentation of nine items, we can expect some forgetting from STM when subjects are waiting for the partial-report cue, or when attempting to recall all nine items. Furthermore, when the partial-report task was conducted without the earlier confounding present in the Darwin et al. study (Massaro, 1976), there was no evidence for a sensory holding of information on the order of seconds. Thus, we reach the intriguing conclusion that visual and auditory sensory storage both have a lifetime of about 250 ms.

D. Estimation of Auditory Persistence

If our auditory experience outlasts the sound producing it, then we should overestimate the perceived duration of the auditory event. This result has been documented in several experiments. Auditory persistence appears to function in an analogous way to visual persistence. An auditory stimulus is presented followed by the onset of a light and the participant states whether the light occurred before the offset of the sound. Efron (1970a) found that subjects estimated the duration of a tone that was actually shorter than 130 ms to be around 130 ms. Gol'dburt (1961) and Massaro and Idson (1978) found that the perceived duration of a short tone was decreased by a following tone, with the influence of the second tone decreasing with increases in the silent interval between the two tones. Von Bekesy (1971), influenced by similar results, stated that "If we assume that every stimulus starts a process in the brain which last perhaps 200 milliseconds, . . . and if we further suppose that this process can be inhibited at any moment during the 200-millisecond interval by the onset of the second stimulus" (p. 530). Thus, the results on auditory persistence are consistent with those on visual persistence.

E. Inverse-Duration Effect

These same experiments, however, also found an inverse-duration effect: subjects overestimated the duration of a short sound more than that of a longer sound (Efron, 1970a). If auditory sensory store is simply a fixed appendage tacked onto the end of an auditory stimulus, then we would not expect the overestimation of a sound's duration to vary with its duration. In order to describe this result, however, it is necessary to consider the perceptual processing of the sound stimulus, not simply its duration. One of the early themes of the ABRM research revolved around the assumption of continuity between processing during the test stimulus itself and during the silent interval afterward. That is, the processing time in Equation (1) was always defined as the total presentation duration plus the ISI. In an extreme test of this idea, Massaro (1974) contrasted two conditions. In the standard silent ABRM condition, a 26-ms vowel was presented and followed by a masking vowel after a variable ISI. In the continuous condition, the same processing intervals were used except that the test vowel was simply left on until the onset of the masking vowel.

Figure 4 shows that the time course of recognition is similar in the two conditions. The continuous condition benefits somewhat from the additional duration, but the masking function asymptotes at the same time as in the silent condition. The overall advantage of the continuous condition can be attributed to a difference of information. A vowel presented for a very

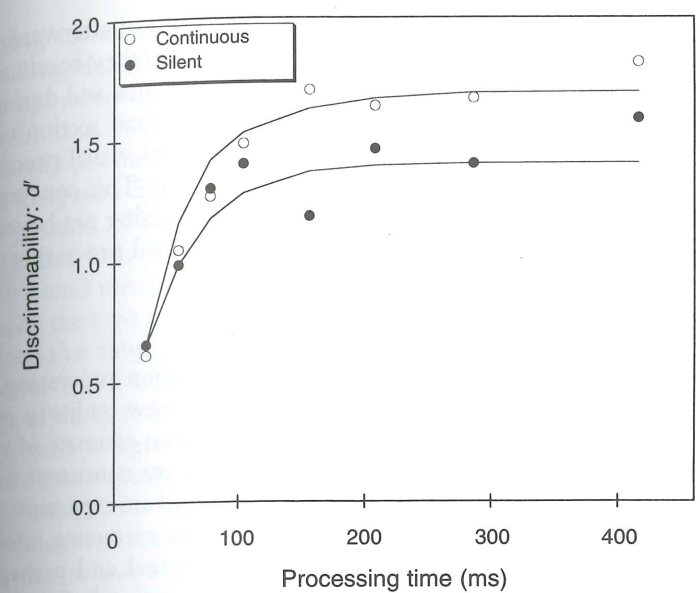

FIGURE 4 Identification of the test vowel /I/ (measured in d' units) as a function of processing time during the continuous vowel presentation or during the silent interval after a 26-ms vowel presentation. The points are the observations and the lines are the predictions given by Equation (1).

short duration necessarily has less information than a vowel presented for a somewhat longer duration because of temporal integration, the auditory system's capability of integrating sound across intervals of 50–60 ms. Independently of the stimulus information, however, the auditory system still requires time for perceptual processing. This processing can occur either during the test stimulus itself or during the silent processing time after its presentation. Thus, we obtain the similar masking functions in the silent and continuous processing conditions, as shown in Figure 4.

Zwislocki's (1969) model of auditory information processing (see Cowan, 1984) cannot predict the inverse duration effect. In this model, neural activity is integrated over time. An auditory stimulus triggers a peripheral neural response. The response is largest at onset, decreases to an asymptote at around 200 ms, remains at this level until the end of the stimulus, and then decays exponentially. This model predicts, as do the traditional models of iconic store, that the duration of the echoic store remaining after stimulus offset should be independent of stimulus duration. Both the inverse-duration effect and the ABRM results falsify this prediction.

These results illustrating the similarities in auditory information processing during the stimulus presentation and the silent interval afterward went mostly unnoticed by the students of iconic store. Thus, they continued to make a distinction between processing during the stimulus and during the period after its offset. However, as we discuss in the final section of this chapter, recent developments have brought the view of visual processing much closer to the existing one for auditory processing. This convergence on analogous mechanisms for auditory and visual processing can be considered to be an advance in our understanding of perceptual processing.

F. Conclusion

Auditory information processing, like visual information processing, is a time-extended process that can be interrupted by a new auditory event. Three different experimental paradigms converge on an estimate of about 250 ms for the duration of this process. The results are consistent with a model that assumes that properties of an auditory sound are represented in a central sensory storage. Perceptual processing involves extracting information from this representation and achieving a perceptual and perhaps an abstract representation. A second auditory event, occurring before the extraction is complete, will necessarily disrupt any additional processing. This conceptualization is rewardingly exactly analogous to the conclusions we reach in our discussion of recent advances in the analysis of iconic memory in the next section.

III. CHANGING CONCEPTIONS OF ICONIC MEMORY

The relatively simple conception of iconic memory that we have described began to change as a result of a number of influential articles that appeared in the early 1980s. In particular, some new empirical findings cast doubt on the icon as a passively decaying informational repository; a review by Coltheart (1980) questioned the unity of icon-as-information repository and icon-as-phenomenological experience; and a philosophical polemic by Haber (1983) questioned iconic memory as even being a suitable topic of scientific research. In this section, we discuss these issues in turn.

A. Inverse-Duration Effects

The counterintuitive phenomenon, known as the inverse-duration effect discussed earlier for auditory processing, was reported by a number of investigators including Bowen, Pola, and Matin (1974) and Efron (1970a, 1970b), who found that the duration of the iconic image, as measured by a synchrony-judgment task, decreased with increasing stimulus duration. Although this finding was rather at odds with the concept of a passively decaying iconic image, the prevailing concept of the icon went largely unchallenged until Di Lollo's (1980) research using an entirely different task, the temporal-integration task, first introduced by Eriksen and Collins (1967).

In this task, two visual stimuli, or frames, are shown in rapid succession, separated by some ISI. Each frame consists of 12 dots in 12 unique positions of an imaginary 5 × 5 grid, and the subject's task is to report the missing dot's position. If both frames are presented simultaneously, no matter how briefly, this task is trivially easy. Replicating previous studies, Di Lollo (1980) found missing-dot identification performance to decrease as the ISI between the two frames increased. The traditional interpretation of these results is that subjects need perceptually to integrate the two frames in order to perceive and report the letters: with a sufficiently short ISI, the iconic image of the first frame is still present when the second frame is presented; hence such integration is possible. As ISI increases, however, the first frame's iconic image presumably continues to diminish, thereby decreasing the probability that the two frames can be perceptually integrated. Creating problems for this interpretation, however, was Di Lollo's new result that performance also decreased as the duration of the first frame increased. This finding strongly disconfirmed the conception of the icon as a passively decaying store; instead, it appeared that iconic decay was also tied intimately to the onset, rather than to just the offset, of stimulus presentation. Based on these results, Di Lollo proposed that the visible persistence resulted not from a passive informational store, but from perceptual activity that began at the time of stimulus onset and diminished in magnitude as processing continued, as in our analysis of auditory processing. We return to this intriguing proposal in a later section.

B. The Splitting of the Icon

As part of an extensive review article, Coltheart (1980) strongly argued against the proposition (previously considered self-evident) that icon-as-information repository and icon-as-phenomenological experience issue from the same perceptual event. The central thrust of Coltheart's argument was that while some techniques for measuring the icon's duration (the synchrony-judgment task and the temporal-integration task) showed the just-described inverse-duration effect, the seminal measurement technique—the partial-report task—did not show such an effect. Accordingly, Coltheart argued, the two types of tasks must be measuring different entities. Coltheart suggested that the concept of an icon be split into (at least) two logically distinct phenomena. He suggested informational persistence as the term for icon-as-information repository, as measured by the partial-report task, and visible persistence as the term for icon-as-phenomenological appearance, as measured by visible-persistence tasks.

C. The Icon's Demise

Haber (1983) deftly finessed all extant difficulties having to do with investigating the icon by arguing that it was an inappropriate subject for scientific investigation to begin with. This unusual position issued from the "ecological validity" perspective (see also Neisser, 1976), a central tenet of which was that any alleged process should be studied only insofar as it had an obvious role in everyday, "real-life" activity. The icon, according to Haber, did not fulfill this criterion, being useful only for the ecologically infrequent activity of "reading during a lightening storm."

Haber's critique did leave investigators somewhat on the defensive, seeking, in an attempt to provide themselves with a worthwhile *raison d'etre*, a purpose for the object of their investigation. During a time of some excitement, for instance, it was believed that persistence was instrumental in maintaining the image obtained during a given eye fixation long enough for it to be integrated with images of subsequent fixations, thereby providing a solution to the mystery of how a stable perception of an ever-retinally-changing visual world was maintained. However, this idea was shown to be untenable (Irwin, 1991, 1992; Rayner & Pollatsek, 1983). The subsequent fixation functions as a masking event for the previous fixation in the same manner that a following stimulus can mask an earlier stimulus in the backward masking task. (If anything, this finding supports the ecological validity of masking experiments because normal successive eye movements can be thought of as successive masking events.)

D. Informational versus Visible Persistence

Despite Haber's broadside, research on persistence did not cease. In response to Coltheart's (1980) suggestion, however, several recent research endeavors have addressed the issue of whether the icon-as-informational repository and icon-as-phenomenological appearance should be viewed as unitary phenomena. Intuitively, the case for conceptualizing informational persistence and visible persistence as having a single basis seems quite compelling. Furthermore, Coltheart's (1980) arguments against this idea were not airtight. His principal reason for postulating informational persistence and visible persistence as different entities revolved around the difference between the effects of stimulus duration on partial report (duration seemed not to have an effect on partial report) versus duration's strong negative effect on visible persistence as measured by synchrony judgment or temporal integration. Recently, this central distinction has been challenged in two ways. First, evidence showing a lack of a duration effect in partial report had in fact been rather sparse, and recently Di Lollo and Dixon (1988, 1992; Dixon & Di Lollo, 1994) have shown that under appropriate conditions,

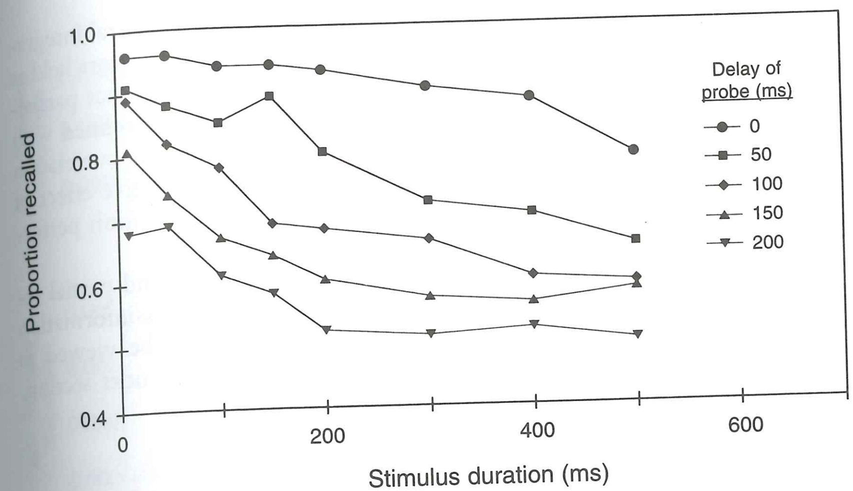

FIGURE 5 Results of Di Lollo and Dixon (1988). Performance in a partial-report task declines with increases both in stimulus-probe ISI and in stimulus duration.

there is a rather robust relation between stimulus duration and partial-report performance. Figure 5 shows results from a partial-report task in which Di Lollo and Dixon (1988) varied both (the usual) stimulus-probe ISI and also the stimulus duration. As expected, partial-report performance declined with increases in ISI; the new and unexpected result was that it also declined quite dramatically with increases in stimulus duration. Thus, contrary to Coltheart's original supposition, an inverse-duration effect is, at least in some circumstances, common to tasks measuring phenomenological appearance on one hand, and available information on the other.

The second difficulty with Coltheart's (1980) arguments is that they were based on the comparison of data from different experiments. This practice can lead to serious interpretational difficulties. To illustrate, suppose a partial-report task in which stimulus duration was varied (e.g., Sperling 1960) is compared with a synchrony-judgment task in which stimulus duration was varied (e.g., Efron, 1970b). While stimulus duration did indeed vary in both experiments, the experiments differed in many other ways as well: for instance, they involved different stimuli, observers, duration ranges, luminances, and contrasts. The consequences of these confoundings is that differences in the reported duration effects (Sperling's null effect vs Efron's inverse-duration effect) cannot be unambiguously attributed to any one element, namely, stimulus duration. For example, Sperling's null results come from a whole-report task in which performance could be data limited because of STM. Loftus and Irwin (in progress) attempted to address this difficulty by conducting experiments in which two tasks, temporal integration and partial report, were directly compared with all other factors held as constant as possible. They found (as did Di Lollo and Dixon) that partial-report performance, like temporal-integration performance, declined with both stimulus duration and ISI. Even so, the over-conditions correlation between the two tasks was far from perfect; briefly, the negative effect of stimulus duration was far more dramatic for temporal-integration performance than for partial-report performance.

Although stimulus duration affects temporal integration and partial report somewhat differently, this does not mean that icon-as-information repository and icon-as-phenomenological appearance must be viewed as entirely distinct and independent phenomena. Indeed, in the next section, we describe a new theory that integrates these phenomena.

IV. A LINEAR-SYSTEMS APPROACH TO PERSISTENCE

In this section, we describe a recent conceptual advance in the study of informational and visible persistence (Loftus & Ruthruff, 1994). We begin with the physical representation of a briefly presented stimulus. Suppose a stimulus (such as a black-on-white letter display) is presented for a brief time period, say 40 ms. The visual system's reaction to this physical stimulus can be described as a linear temporal filter that maps the stimulus wave form into what we shall call a sensory response (see Watson, 1986, for an excellent review of linear systems from a vision science perspective). Consider first the system's response to a very brief bright stimulus called an impulse. An impulse is assumed to produce what is referred to as an impulse–response function that relates the magnitude of some stimulus-signaling neural event to the time since the impulse's occurrence. A widely accepted form of the impulse–response function is shown in Figure 6A. Here, the impulse is shown as the vertical line on the left, while the system's response to it lags behind, rising to a maximum after about 50 ms, and then decaying back to 0 after about 250 ms.

Now consider a real stimulus (as opposed to an impulse), such as the 40-ms stimulus of Figure 6B. We can conceptualize this stimulus as divided into a series of four successive 10-ms impulses, starting at times 0, 10, 20, and 30 ms following stimulus onset. Now each impulse generates its own independent impulse–response function, starting at times 0, 10, 20, and 30 ms, respectively, as shown in Figure 6C. Finally—and this is the "linear" part—the individual "impulse–response functions" are assumed to sum to provide the overall sensory–response function, depicted by the heavy line in Figure 6C, and depicted again in Figure 6D.

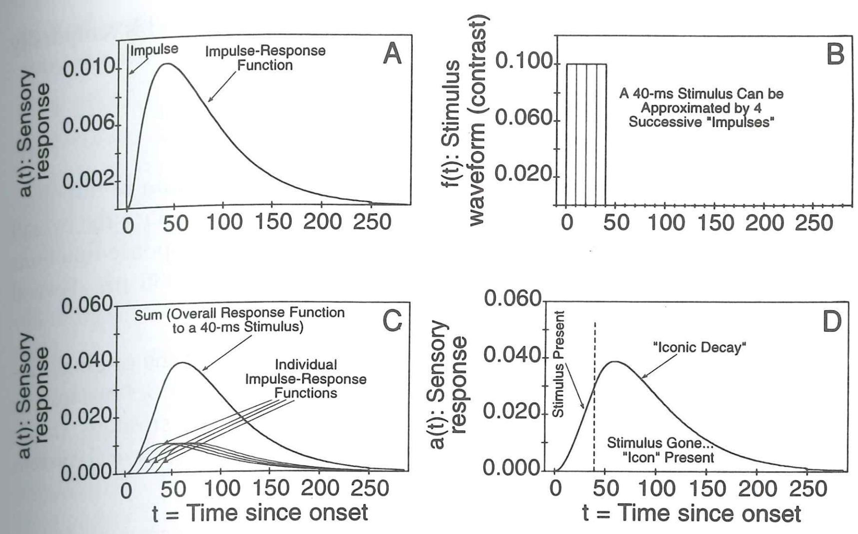

FIGURE 6 Generation of a sensory-response function. (A) Response to an "impulse." (B) A stimulus wave form can be conceptualized as a train of impulses. (C) Individual impulse–response functions sum to generate overall sensory-response function. (D) The sensory-response function generated by a linear temporal filter applied to the stimulus wave form. This curve should be compared to the corresponding curve of Figure 1.

A. The Diminished Status of "Iconic Decay"

The sensory-response function of Figure 6D is analogous to the curve originally shown in Figure 1 in the sense that it is meant to show the entire time course of some fundamental perceptual process that results from a brief visual presentation. Unlike the curve in Figure 1, however, this sensory-response function is derived from simple basic principles. In Figure 6D, the pre-stimulus-offset and post-stimulus-offset portions of the sensory-response function have been labeled analogously to Figure 1; again, the post-stimulus portion of the curve has been labeled "iconic decay." At this point, however, the entire concept of "iconic decay" starts to become somewhat moot. That is, the interest shifts to the entire sensory-response function; stimulus offset is not a particularly important event and accordingly it makes little sense to concentrate on only that portion of the sensory response that happens after stimulus offset. Earlier we noted that, since the time of Sperling's original work, psychologists have viewed the icon as a somewhat mysterious perceptual appendage, lurking around after stimulus offset, crying out to be "explained." With the conceptualization depicted in Figure 6, the icon's mystery evaporates: it occurs simply because the visual system, like most systems, has an output that lags behind and is temporally blurred relative to its input.

B. Consequences of Linearity

Any arbitrary stimulus wave form can be broken into a train of impulses, and the resulting impulse–response functions added to produce the overall sensory-response function. Figure 7 shows the sensory-response functions to six different stimuli ranging in duration from 20 to 480 ms. Several aspects of these functions are noteworthy.

1. A major difference between the Figure 7 curves and the original Figure 1 curve is that the magnitude of the sensory response does not leap to some greater-than-zero value instantaneously following stimulus onset; rather it rises gradually. This makes sense; virtually no physical system responds instantaneously to some input.

2. For a given intensity, the curve's maximum value increases with increasing stimulus duration.

3. Decay of the sensory response does not begin immediately at stimulus offset, but rather at some time following stimulus offset. This is most easily seen with short stimuli.

4. The sensory-response functions for longer duration stimuli appear similar to the original conception of iconic processing depicted in Figure 1:

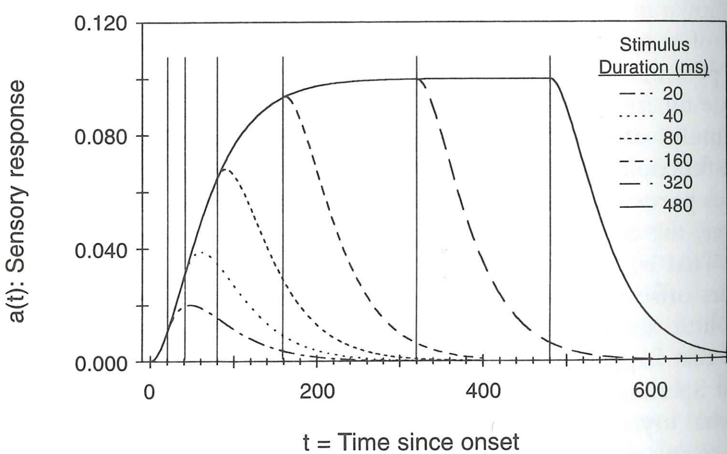

FIGURE 7 Sensory-response functions resulting from six stimulus durations. Vertical lines indicate stimulus offsets.

in both cases, the perceptual response remains at a relatively stable level until the stimulus ends and then starts more or less immediately to decay.

5. This view of "iconic memory" makes no distinction between perceptual events that occur before or after stimulus offset; rather, all that is important for subsequent processing is the height of the sensory-response function, regardless of whether it is established before or after the time of physical stimulus offset.

C. Applications of the Linear-Filter Model to Visible Persistence

We briefly describe the applications of the linear-filter model to visible persistence as measured by temporal integration and synchrony-judgment tasks. Earlier, we described the inverse-duration effect in a temporal-integration task by Di Lollo (1980) in which performance was found to decline dramatically as the duration of Frame 1 increased. More recently, however, Dixon and Di Lollo (1992, 1994) reported another new and surprising finding: Performance also declines as dramatically with increases in Frame 2 duration. Even more surprising, Dixon and Di Lollo (1994) found an analogous effect in a partial-report task. As in the earlier Di Lollo and Dixon (1988) partial-report experiment, Dixon and Di Lollo used a circular array of 15 letters presented for durations ranging from 20 to 320 ms. Immediately following the display's offset, a visual probe signaled which letter was to be reported. The probe's duration also varied from 20 to 320 ms. As in the temporal-integration experiment, partial-report performance declined with both array duration and probe duration.

To account for these various effects, Dixon and Di Lollo (1994) offered a theory that centered on the temporal similarity in the visual system's responses to each of two successively presented stimuli. Although this theory predicted the results from a variety of temporal-integration and partial-report tasks quite well, it is not clear how it would account for other visual phenomena, such as the inverse-duration effect obtained in a synchrony-judgment task. On the other hand, Loftus and colleagues (e.g., Loftus & Hanna, 1989; Loftus & Hogden, 1988; Loftus & Irwin, 1994) have applied the linear-filter model successfully to both synchrony judgment and temporal integration, as well as to partial-report tasks. To do so, they envisioned the subject to be extracting information at some instantaneous rate, where the magnitude of the information-extraction rate at time t is determined by the product of two things: the magnitude of the sensory response at that time and the amount of as-yet-to-be extracted information left in the stimulus at that time. The first influence dictates that rate depends on the sensory response. The second influence embodies a kind of "diminishing-returns" idea, as in Equation (1): the more information that has been extracted from the stimulus already, the less remaining new information. "Phenomenological appearance" is identified with this information-extraction rate: the assumption being that the slower the subject is extracting information, the less the subject will be consciously aware of the stimulus.

Figure 8 shows how these assumptions successfully account for the inverse-duration effect in a synchrony-judgment task. The general idea is that the subject will judge the stimulus as having phenomenologically disappeared at the time that the information-extraction rate falls below some criterion level. The 40-ms information-extraction rate function falls faster following its offset than does the 20-ms information-extraction rate function. This is because there is less yet-to-be-extracted information at the time of offset for the 40-ms than for the 20-ms stimulus. A consequence of this faster fall is that the 40-ms function crosses the same criterion sooner following its offset than does the 20-ms function. The times elapsing between stimulus offset and when the information-extraction rate functions fall below the criterion are indicated by the double-headed arrows in the figure (solid and dashed, respectively, for the 20-ms and 40-ms presentations). This time is obviously longer for the 20-ms presentation, thus accounting (at least qualitatively) for the inverse-duration effect in a synchrony-judgment task. This account also predicts that the perceiver would not become aware of the stimulus until some short time after its onset.

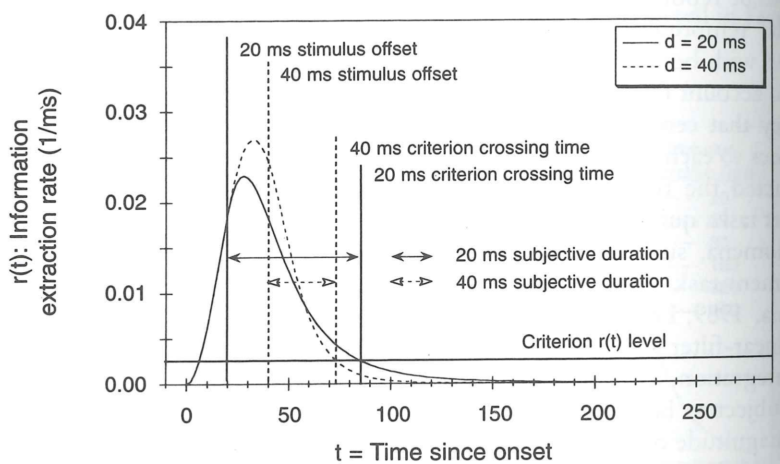

FIGURE 8 The information-extraction rate theory's explanation of the inverse-duration effect in a synchrony-judgment experiment. The two curves represent $r(t)$ functions for a 20-ms and a 40-ms stimulus. The two left-hand vertical lines represent time of stimulus offset, while the two right-hand vertical lines represent times that the $r(t)$ functions fall below the $r(t)$ criterion level. Two-headed arrows represent persistence duration, which is longer for the 20-ms stimulus than for the 40-ms stimulus.

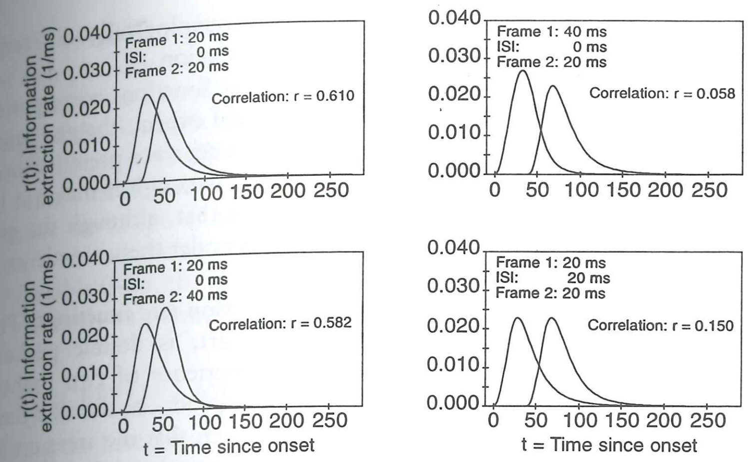

FIGURE 9 The correlation explanation of information-extraction rate theory of temporal-integration performance.

To account for the previously described temporal-integration effects, Loftus and Irwin (1994) borrowed the temporal similarity assumption from Dixon and Di Lollo's theory; however, Loftus and Irwin applied the technique to the information-extraction rate functions rather than to the sensory-response functions. Accordingly, their account of temporal integration is quite similar to Dixon and Di Lollo's. Figure 9 shows the result of this exercise. It is quite apparent that, as with Dixon and Di Lollo's theory, the correlation between the two information-extraction rate functions decreases with increases in Frame 1 duration, ISI, and Frame 2 duration.

Thus, the linear-systems approach can account for the visible-persistence phenomena. Now we describe the application of the approach to information extraction, and we also demonstrate a proposed theoretical relation between visible persistence and available information. In a picture-memory experiment, complex, naturalistic, colored pictures were shown, one at a time, in a "study phase" to a group of subjects (Loftus, in preparation). Each picture was shown in one of two conditions: Either it was shown once for 100 ms, or it was shown twice for 50 ms apiece with an ISI of 250 ms. For ease of exposition, these conditions are referred to as the "no-gap" and the "gap" conditions. The amount of information extracted from the pictures was assessed by memory performance in a later recognition test.

Two important results emerged. First, subjects were able to distinguish pictures in the gap condition from pictures in the no-gap condition with 100% accuracy. In the gap condition, the picture appeared to flash twice, while in the no-gap condition, the picture appeared to flash only once. Second, later memory performance was identical for the two study conditions. Although the two conditions were phenomenologically different, they produced the same degree of information extraction.

Figures 10A and B show the $a(t)$ sensory-response functions corresponding to the gap and no-gap conditions. As one would expect, the gap function has two distinct peaks resulting from the two separate presentations, while the no-gap function has only a single peak. Although it may not be immediately obvious, a consequence of linearity is that, although the gap and no-gap curves are of different shapes, the areas under them are identical (areas of 10.00 in both cases).

Figures 10C and D show the information-extraction rate functions. The gap function, like its sensory-response counterpart, is double peaked, which, according to the theory produces the experience of two flashes. Correspondingly, the single-peaked gap function produces the one-flash experience that occurs in the no-gap condition. Given that the areas under the two information-extraction rate functions are identical and that the total area under any extraction-rate function corresponds to the total amount of whatever it is that is being extracted, the amounts of extracted information are, according to the theory, identical in the gap and the no-gap conditions. Therefore, the theory correctly predicts memory performance to be identical in the two conditions.

The point of this discussion has been to underscore the idea that this information-extraction rate theory affords some degree of unity between the two important psychological events that we have been discussing: information extraction and phenomenological appearance. Within this theory, the two phenomena are both direct consequences of the same information-extraction rate function. Phenomenological experience corresponds to the shape of the function, while information extraction corresponds to the area under the function. Coltheart was correct that the two phenomena behave in somewhat different ways. According to the present theory, this occurs because the shape of a function and the area under the function likewise behave in somewhat different ways. But they are both aspects of, and predictable from, the same unitary sensory-response function. We now turn to the study of perceptual memory.

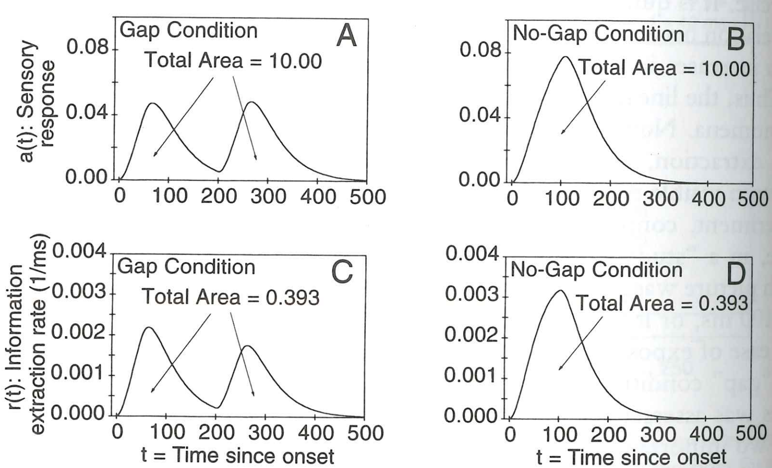

FIGURE 10 The information-extraction rate theory's explanation of the "gap" experiment described in the text. (A, B) $a(t)$ Functions for the no-gap and gap conditions. (C, D) Corresponding $r(t)$ functions. Phenomenological appearance is determined by the shape of the $r(t)$ functions, while extracted information is determined by the area under the functions.

V. PERCEPTUAL MEMORIES

During the first decades of cognitive research, most of the field appeared to be intrigued by the loss of information from the initial iconic store. There was little concern for how the sensory information was processed and transferred to a more stable perceptual memory. The birth of the suffix effect and its cottage industry appears to have been due to John Morton's visit at Yale with the heretical hypothesis that the modality of a list of items would have important consequences for memory (Crowder & Morton, 1969). Perceptual and memory researchers tended to study either sensory storage or verbal (abstract) memory. Recently, only one investigator has stressed the importance of perceptual memory in accounting for information processing (Cowan, 1984, 1988). Massaro (1975a), on the other hand, devoted three chapters in his textbook to auditory and visual perceptual memory: After describing how familiarity in perceptual memory is central to the recognition of an event as one that has been experienced previously, the time course of the perceptual memory for auditory nonspeech and speech signals and visual events was presented. We shall briefly illustrate several prototypical results taken from these chapters because they are as relevant today as they were in 1975 (if not more so).

A. Auditory Perceptual Memory

Significant perceptual memory of a preceding auditory event can remain even after extended processing of a new event. This phenomenon has been illustrated in several memory-for-pitch tasks. For example, Wickelgren (1969), using a delayed comparison task in which a standard tone is followed by a comparison tone after a variable ISI (see Massaro, 1975a, p. 478), and an interference tone is presented during the ISI, found that forgetting of the standard tone followed a negatively decreasing exponential function but that significant memory remained after three minutes of the interference tone.

Another study illustrating the contribution of perceptual memory in verbal memory was carried out by McNabb and Massaro (described in Massaro, 1975a, p. 508). They presented a sequential list of one-syllable words on a memory drum, and subjects repeated the words as they were presented either subvocally or vocally. The list was followed by a visually presented test word and the recognition memory test required subjects to indicate whether the test word had occurred on the preceding list. Memory benefited from the vocal reading of the test list and this benefit was independent of the number of items between the original presentation and test. In this case, perceptual memory appeared to last at least 15 seconds or so. This result and a variety of other results (see Greene, 1992, chap. 2) appear to show that the life span of auditory perceptual memory is not limited to just a few seconds.

B. Visual Perceptual Memory

Perceptual memory is not limited to auditory and speech signals, but has also been demonstrated for visual information. The last two decades have witnessed a revival of the positive contribution of visual imagery on memory (Finke, 1989). Scarborough (1972) had previously found that less forgetting occurred in the Peterson and Peterson (1959) task when the test items were presented visually rather than auditorily. The interference task was counting aloud backward by threes so the advantage of the visual presentation mode is reasonable. Additional evidence for a variety of perceptual memories has been documented by Massaro (1975a) and Cowan (1984).

C. Models of Perceptual Memory

Massaro (1970a) had concluded that the evidence for perceptual memory and abstract STM could be described within the same information processing model. Baddeley and Hitch (1974) suggested that STM should be thought of as a working memory but with multiple subsystems controlled by a limited capacity executive (see also Baddeley, 1986; Nairne, this volume, Chapter 4). They pinpointed two important subsystems: a visuospatial scratch pad and an articulatory loop. However, there is nothing to preclude other subsystems, such as auditory and tactile memories. Furthermore, the evidence Baddeley and Hitch brought in favor of an articulatory memory cannot account for the advantage usually found for an auditory presentation relative to a visual one, as phonological or articulatory encoding should be equally engaged for both spoken and written language.

Cowan (1984, 1988), in a thorough review, has provided evidence for two types of sensory storage, which parallel the preperceptual and synthesized memories previously postulated by Massaro (1975a). The preperceptual store holds information for the initial stage of processing called perception. Perception, however, entails much more than simply an abstract categorization of the environmental event: It provides a perceptual representation that supports behavioral action. This perceptual representation can be exposed in a variety of ways as described in the previous section. Cowan (1988) has also acknowledged the modality-specific dimensions of STM. Contrary to abstract memory, modality-specific memories easily hold continuous information. The initial sensory store of roughly 250-ms duration differs from the modality-specific (perceptual) dimensions of STM. As pointed out by Cowan, the perceptual and abstract dimensions of STM have much more in common than either of these dimensions have with the initial 250-ms sensory store.

D. Implicit Memory

In some respects, this earlier research on perceptual memory anticipated the implicit memory paradigm shift of the last decade. It has shown that perceptual processing during study and the retention of these perceptual events influenced later recognition memory and recall. That is, this research had demonstrated that performance cannot be adequately described on the basis of only abstract symbolic representations. Rather, our sensory and perceptual interactions necessarily provide the groundwork for symbolic processing and memory.

The research on implicit memory during the last decade has awakened the field to the importance of perceptual memory (Crowder, 1993; Graf & Masson, 1993). Our perceptual experiences and perceptual memories provide the interface between sensory storage (our earlier visions of echoic and iconic memory) and some symbolic encoding. Roediger and Srinivas (1993) provide a nice demonstration of how previous perceptual experience is central to recognizing ambiguous figures, such as the famous dotted dalmation. Experience with ambiguous figures, such as the Street figures, the dotted dalmation, and the close-up view of a cow, makes these easier to see and recognize. Roediger and Srinivas (1993) describe these results in terms of transfer-appropriate processing. In extant memory research, participants show the largest influence of previous experience when the current situation most closely matches the earlier processing experience. The ambiguous figures and their recognition simply emphasize the important role of perceptual processing and perceptual memory in prototypical behaviors such as visual navigation, understanding speech and music, and reading.

E. Symbolic Representation and Perceptual Memory

Although it is difficult to impose historical rationality on previous work, it is reasonable to blame the computer metaphor for the neglect of perceptual memory. Computers do their most intelligent work with abstract symbols; why would not intelligent humans do the same? The prototypical information processing model was therefore directed at transforming the concrete stimulus information into an abstract form as quickly as possible. This perspective resulted in the notion of a sensory store interfaced to an abstract STM. Psychologists seemed to forget that our sensory grounding could provide valuable support for information processing. Even much of speech research was wedded to the symbol metaphor. Pisoni (1993) has recently criticized speech research for slighting modality-specific phenomena, such as the decrement in speech perception and memory when the perceiver is confronted with multiple speakers (talkers) relative to just one.

The relative contribution of perceptual and symbolic processes can be appreciated in an ingenious experiment carried out by Epstein and Rock (1960). Recency of experience and expectancy of events to come are factors consistently used to explain performance variations. The authors were interested in the relative influence of recency and expectancy in the perceptual interpretation of Boring's wife/mother-in-law figure. Subjects identified the two unambiguous forms presented one at a time in a sequence of alternations. Then at some point, the ambiguous version of this figure was substituted for one of the unambiguous figures. Given that the last presentation had been the unambiguous mother-in-law, would the participants identify the ambiguous figure in terms of what they had most recently experienced or in terms of what they expected? One might say there should be a symbolic anticipation of the wife but a perceptual memory of the mother-in-law. In favor of the perceptual over the symbolic, subjects identified the ambiguous figure as equivalent to what they had just perceived (the mother-in-law).

VI. MEMORY STORES AND INFORMATION PROCESSING

In his retrospective glance at iconic storage, Neisser (1976) asked the question whether it was in the observer or the environment. His justified complaint was that cognitive theorists treat the icon as if it were a picture, independent of the perceptual mechanisms that "look at it." With the hindsight of contemporary inquiry, we understand that any storage of information is inextricably bound up with the processing of that information. Sanders (1993) reminds us that delimiting a sequence of processing stages is only a preliminary heuristic. Given this start, one can proceed to develop more precise process models. Horst Mittelstadt (personal communication) advises that each box in the sequence contain a dynamic equation. By this view, information processing stage (box) models are acceptable as long as there is an equation yoked to each box. The equation would naturally describe the processing of the "stored" information.

A. Structure versus Process: Can We Do with Stores?

Simple studies of perceptual memory appear to be relevant to the structure/process issue. A well-worn psychophysical task that proved productive in the study of auditory perceptual memory was delayed comparison. A standard tone is followed after some intervening event or activity by a comparison tone (Massaro, 1970b; Wickelgren, 1969). The participant responds whether the comparison was the same or different from the standard. With a roving standard that fluctuates from trial to trial and a highly similar comparison tone to preclude any value of verbally encoding the standard, how do we describe performance without assuming some storage of the standard in memory? At some level, the current processing of the comparison must be compared to some representation of the standard. This simple task might convince most investigators of the need for structure as well as process in their description of perception and memory. Is it sufficient to say that a comparison tone is recognized as the same as the previous standard because the comparison is more easily processed?

As articulated by Freyd (1987), a structure process dualism remains central to many information processing theories. But she questions whether computation in real time utilizes structures distinct from processes. To clarify this dualism, consider the classical view of a preperceptual storage such as iconic or echoic memory. This view implies a temporary representation of a stimulus presentation (the proximal form of the distal event). The perceptual process, as described as some function of time, then "reads out" from this structure. For example, an exponential readout is commonly supported because the absolute gain in performance diminishes with increases in processing time. It appears to be more penetrating to describe both structure and process rather than to reduce the description to just process. The linear systems analysis of visual processing (described in the preceding section) provides a worthy example of the need for both structure and process. The magnitude of the sensory event serves as the structure for several different processes: information extraction and phenomenal appearance.

B. Stage Models and Multiple Representations

To justify the initial sensory storage as distinct from following processing stages and other perceptual representations, it is necessary to clarify the information processing framework. We have evidence that information can be maintained in memory at multiple levels and in various forms. This parallel storage of information does not negate the sequential stage model, however. What is important to remember is that transfer of information from one stage to another does not require that the information is lost from the earlier stage. Reading a word does not obliterate its visual representation. For our purposes, we now understand that the representation of an earlier processing stage maintains its integrity even after it has been "transformed" and transmitted to the following processing stage. Thus, it is entirely reasonable to have multiple perceptual and abstract representations within stage models of information processing (e.g., Baddeley, 1986; Massaro, 1975a).

Acknowledgments

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References

Averbach, E., & Coriell, H. S. (1961). Short-term memory in vision. *Bell Systems Technical Journal, 40,* 309–328.
Averbach, E., & Sperling, G. (1961). Short-term storage in vision. In C. Cherry (Ed.), *Symposium on Information Theory* (pp. 196–211). London: Butterworth.
Baddeley, A. D. (1986). *Working memory.* Oxford: Clarendon Press.
Baddeley, A., & Hitch, G. J. (1974). Working memory. In G. Bower (Ed.), *Recent advances in learning and motivation* (Vol. VIII, pp. 47–90). New York: Academic Press.
Bland, D. E., & Perrott, D. R. (1978). Backward masking: Detection versus recognition. *Journal of the Acoustical Society of America, 63,* 1215–1220.
Bowen, R. W., Pola, J., & Matin, L. (1974). Visual persistence: Effects of flash luminance, duration and energy. *Vision Research, 14,* 295–303.
Breitmeyer, B. G. (1984). *Visual masking: An integrative approach.* New York: Oxford.
Coltheart, M. (1980). Iconic memory and visible persistence. *Perception & Psychophysics, 27,* 183–228.
Cowan, N. (1984). On short and long auditory stores. *Psychological Bulletin, 96,* 341–370.
Cowan, N. (1987). Auditory sensory storage in relation to the growth of sensation and acoustic information extraction. *Journal of Experimental Psychology: Human Perception and Performance, 14,* 204–215.
Cowan, N. (1988). Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information processing system. *Psychological Bulletin, 104,* 163–191.
Crowder, R. G. (1993). Auditory memory. In S. McAdams & E. Gigand (Eds.), *Thinking in sound: The cognitive psychology of human audition* (pp. 113–145). Oxford: Oxford University Press.
Crowder, R. G., & Morton, J. (1969). Precategorical acoustic storage. *Perception & Psychophysics, 5,* 365–373.
Darwin, C. J., Turvey, M. T., & Crowder, R. G. (1972). An auditory analogue of the Sperling partial report procedure: Evidence for brief auditory storage. *Cognitive Psychology, 3,* 255–267.

Di Lollo, V. (1980). Temporal integration in visual memory. *Journal of Experimental Psychology: General, 109,* 75–97.
Di Lollo, V., & Dixon, P. (1988). Two forms of persistence in visual information processing. *Journal of Experimental Psychology: Human Perception and Performance, 14,* 671–681.
Di Lollo, V., & Dixon, P. (1992). Inverse duration effects in partial report. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 1089–1100.
Dixon, P., & Di Lollo, V. (1992). Effects of display luminance, stimulus type, and probe duration on visible and schematic persistence. *Canadian Journal of Psychology, 45,* 54–74.
Dixon, P., & Di Lollo, V. (1994). Beyond visible persistence: An alternative account of temporal integration and segregation in visual processing. *Cognitive Psychology, 26,* 33–63.
Efron, R. (1970a). The relationship between the duration of a stimulus and the duration of a perception. *Neuropsychologia, 8,* 37–55.
Efron, R. (1970b). Effect of stimulus duration on perceptual onset and offset latencies. *Perception & Psychophysics, 8,* 231–234.
Epstein, W., & Rock, I. (1960). Perceptual set as an artifact of recency. *American Journal of Psychology, 73,* 214–228.
Eriksen, C. W., & Collins, J. F. (1967). Some temporal characteristics of visual pattern perception. *Journal of Experimental Psychology, 74,* 476–484.
Finke, R. A. (1989). *Principles of mental imagery.* Cambridge, MA: MIT Press.
Freyd, J. J. (1987). Dynamic mental representations. *Psychological Review, 94,* 427–438.
Gol'dburt, S. N. (1961). Investigation of the stability of auditory processes in micro-intervals of time (new findings on back masking). *Biophysics, 6,* 809–817.
Graf, P., & Masson, M. E. J. (Eds.). (1993). *Implicit memory: New directions in cognition, development, and neuropsychology.* Hillsdale, NJ: Erlbaum.
Greene, R. L. (1992). *Human memory: Paradigms and paradoxes.* Hillsdale, NJ: Erlbaum.
Haber, R. N. (1983). The impending demise of the icon: A critique of the concept of iconic storage in visual information processing. *Behavioral and Brain Sciences, 6,* 1–54.
Hawkins, H. L., & Presson, J. C. (1986). Auditory information processing. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol 2. Cognitive processes and performance* (pp. 26-1–26-64). New York: Wiley.
Hogben, J. H., & Di Lollo, V. (1974). Perceptual integration and perceptual segregation of brief visual stimuli. *Vision Research, 14,* 1059–1069.
Irwin, D. E. (1991). Information integration across saccadic eye movements. *Cognitive Psychology, 23,* 420–456.
Irwin, D. E. (1992). Memory for position and identity across eye movements. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18,* 307–317.
Kallman, H. J., & Massaro, D. W. (1979). Similarity effects in auditory backward masking. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 312–327.
Kallman, H. J., & Massaro, D. W. (1983). Backward masking, the suffix effect and preperceptual auditory storage. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 9,* 312–327.
Loftus, G. R., Duncan, J., & Gehrig, P. (1992). On the time course of perceptual information that results from a brief visual presentation. *Journal of Experimental Psychology: Human Perception and Performance, 18,* 530–549.
Loftus, G. R., & Hanna, A. M. (1989). The phenomenology of spatial integration: Data and models. *Cognitive Psychology, 21,* 363–397.
Loftus, G. R., & Hogden, J. (1988). Picture perception: Information extraction and phenomenological persistence. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 22, pp. 139–191). New York: Academic Press.
Loftus, G. R., & Irwin, D. E. (in press). Visible and informational persistence: Different tasks measure different things. *Cognitive Psychology.*

Loftus, G. R., & Ruthruff, E. (1994). A theory of visual information acquisition and visual memory with special application to intensity-duration tradeoffs. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 33–50.
Lupker, S. J., & Massaro, D. W. (1979). Selective perception without confounding contributions of decision and memory. *Perception & Psychophysics, 25,* 60–69.
Massaro, D. W. (1970a). Preperceptual auditory images. *Journal of Experimental Psychology, 85,* 411–417.
Massaro, D. W. (1970b). Perceptual processes and forgetting in memory tasks. *Psychological Review, 77,* 557–567.
Massaro, D. W. (1972). Preperceptual images, processing time, and perceptual units in auditory perception. *Psychological Review, 79,* 124–145.
Massaro, D. W. (1974). Perceptual units in speech recognition. *Journal of Experimental Psychology, 102,* 199–208.
Massaro, D. W. (1975a). *Experimental psychology and information processing.* Chicago: Rand-McNally.
Massaro, D. W. (Ed.). (1975b). *Understanding language: An information processing analysis of speech perception, reading and psycholinguistics.* New York: Academic Press.
Massaro, D. W. (1976). Perceptual processing in dichotic listening. *Journal of Experimental Psychology: Human Learning and Memory, 2,* 331–339.
Massaro, D. W. (1979). Reading and listening [Tutorial paper]. In P. A. Kolers, M. Wrolstad, & H. Bouma (Eds.), *Processing of visible language* (Vol. 1, pp. 331–354). New York: Plenum Press.
Massaro, D. W. (1987). *Speech perception by ear and eye: A paradigm for psychological inquiry.* Hillsdale, NJ: Erlbaum.
Massaro, D. W. (1989). *Experimental psychology: An information processing approach.* Orlando, FL: Harcourt Brace.
Massaro, D. W., Cohen, M. M., & Idson, W. L. (1976). Recognition masking of auditory lateralization and pitch judgments. *Journal of the Acoustical Society of America, 59,* 434–441.
Massaro, D. W., & Idson, W. L. (1978). Target-mask similarity in backward recognition masking of perceived tone duration. *Perception & Psychophysics, 24,* 225–236.
Mewhort, D. J. K., Campbell, A. J., Marchetti, F. M., & Campbell, J. I. D. (1981). Identification, localization, and "iconic memory:" An evaluation of the bar-probe task. *Memory & Cognition, 9,* 50–67.
Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review, 63,* 81–97.
Moore, J. J., & Massaro, D. W. (1973). Attention and processing capacity in auditory recognition. *Journal of Experimental Psychology, 99,* 49–54.
Neisser, U. (1967). *Cognitive psychology.* New York: Appleton-Century-Crofts.
Neisser, U. (1976). *Cognition and reality.* San Francisco: W. H. Freeman.
Peterson, L. R., & Peterson, M. J. (1959). Short-term retention of individual verbal items. *Journal of Experimental Psychology, 58,* 193–198.
Pisoni, D. B. (1993). Long-term memory in speech perception: Some new findings on talker variability, speaking rate and perceptual learning. *Speech Communication, 113,* 109–125.
Rayner, K., & Pollatsek, A. (1983). Is visual information integrated across saccades? *Perception & Psychophysics, 34,* 39–48.
Roediger, H. L., III, & Srinivas, K. (1993). Specificity of operations in perceptual priming. In P. Graf and M. E. J. Masson (Eds.), *Implicit memory: New directions in cognition, development, and neuropsychology* (pp. 17–48). Hillsdale, NJ: Erlbaum.
Sanders, A. F. (1993). Performance theory and measurement through chronometric analysis. In D. E. Meyer & S. Kornblum (Eds.), *Attention and performance XIV: Synergies in experimental psychology, artificial intelligence, and cognitive neuroscience—A silver jubilee* (pp. 689–699). Cambridge: MIT Press.

Scarborough, D. L. (1972). Stimulus modality effects on forgetting in short-term memory. *Journal of Experimental Psychology, 95,* 285–289.
Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs, 74* (11, Whole No. 498).
Treisman, A. M. (1986). Properties, parts, and objects. In K. R. Boff, L. Kaufmann, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. II. Cognitive processes and performance* (chap. 35). New York: Wiley.
Treisman, A. M., & Gelade, G. (1980). Feature-integration theory of attention. *Cognitive Psychology, 12,* 97–136.
Von Bekesy, G. (1971). Auditory inhibition in concert halls. *Science, 171,* 529–536.
Watson, A. B. (1986). Temporal sensitivity. In K. R. Boff, L. Kaufmann, & J. P. Thomas (Eds.), *Handbook of perception and human performance* (Vol. I, pp. 6-1–6-43). New York: Wiley.
Weichselgartner, E., & Sperling, G. (1985). Continuous measurement of visible persistence. *Journal of Experimental Psychology: Human Perception and Performance, 11,* 711–725.
Wickelgren, W. A. (1969). Associative strength theory of recognition memory for pitch. *Journal of Mathematical Psychology, 6,* 13–61.
Zwislocki, J. J. (1969). Temporal summation of loudness: An analysis. *Journal of the Acoustical Society of America, 46,* 431–440.