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Evolving Conceptions of Memory Storage, Selective Attention, and Their Mutual Constraints Within the Human Information-Processing System

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The purpose of this review is to formulate a revised model of information processing that takes into account recent research on memory storage, selective attention, effortful versus automatic processing, and the mutual constraints that these areas place on one another. One distinctive aspect of the proposed model is the inclusion of two phases of sensory storage in each modality. The first phase extends sensation for several hundred milliseconds, whereas the second phase is a vivid recollection of sensation. The mechanism of at least the longer phase is the activation of features in long-term memory, comparable to the mechanism of non-sensory, short-term storage. Another distinctive aspect of the model is that habituation/dishabituation and central executive processes together are assumed to determine the focus of attention, without the need for either an early or a late attentional filter. Research issues that contribute to a comparison of models are discussed.

Broadbent (1958) proposed a general model of the human information-processing system that was primarily designed to account for how we attend to some stimuli while ignoring others (i.e., our selective-attention capabilities) and how we retain stimulus information, in various forms, both before and after attending to it (i.e., our memory storage capabilities). Although a version of Broadbent's model still appears in almost every textbook of cognitive psychology, researchers today are ambivalent toward it; the model appears to be inconsistent with many research findings. Schneider (1987) noted that "in the 1970s there was a clear movement away" from this sort of model to "a variety of representations (e.g., levels of processing, schemata, semantic networks, and production systems)" (p. 73).

Broadbent's (1958) model of processing can be termed a "pipeline" model, in which information is conveyed in a fixed serial order from one storage structure to the next: from sensory storage to short-term storage and then to long-term storage. Voluntary control of the system was represented by a selective-attention device or "filter" located after the sensory store and by information feedback loops from the high-level processing system to earlier processing stages. Recently, Broadbent (1984) summarized a number of reasons why this sort of model may be obsolete. They include (a) its characterization of the subject as a passive recipient of information, (b) massive "top–down" influences in perception in which higher-level information affects lower-level recognition, seemingly placing an excessive burden in the model upon feedback loops from long-term storage to earlier stages; (c) the inability to represent processing strategies and flexibility in a plausible manner, and (d) logical flaws in methods, such as the additive factor method, that have been used to empirically distinguish between different processing stages in the pipeline. To address these shortcomings, Broadbent (1984) proposed an alternative model in which the stores were arranged in a "Maltese cross" that allowed increased flexibility in the sequence of information transfer. However, some of the commentaries following his article argued that this model may have too many unnecessary degrees of freedom. For example, Crowder (1984) noted that "the bidirectional arrows of the Maltese Cross make it simply a feedback model in which 'anything goes' " (p. 72). The model will be discussed near the end of this article.

None of the alternatives to a pipeline model has been shown to provide an adequate representation of the information-processing system as a whole, at a macroscopic level. The recently popular connectionist approach (Feldman & Ballard, 1982; McClelland & Rumelhart, 1986), which focuses on the parallel, distributed processing of information at a microscopic level of analysis, may apply only to some aspects of processing. For example, Rumelhart, Smolensky, McClelland, and Hinton (1986) proposed that "processes that happen very quickly—say less than .25 to .5 seconds—occur essentially in parallel and should be described in terms of parallel models. Processes that take longer . . . have a serial component and can more readily be described in terms of sequential information-processing models" (p. 56).

More generally, researchers of the memory system have not settled on a view of the selective-attention process that is consistent with the properties of memory, and vice versa. Norman (1968) sketched one view of the system in which memory and attention were considered together. However, even a cursory ex-

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amination of cognitive psychology textbooks (e.g., Best, 1986; Reynolds & Flagg, 1983) illustrates that there has been considerable progress since 1968 on various special aspects of information processing (e.g., perceptual coding, temporal memory decay and interference, mnemonic strategies, long-term memory storage, processing effort, selective attention, and awareness). The main thesis of this article is that a detailed reexamination of the mutual constraints of these different areas upon one another can lead to an improved representation of the processing system.

Organization of the Article

Theoretical difficulties of the original multistore model in accounting for mnemonic and attentional phenomena will be discussed, and possible solutions will be suggested. First, research on the types of memory storage will be reviewed, leading to the suggestion that sensory, short-term, and long-term stores are organized into a system different from the multistore model as originally conceived. Next, the importance of a "central executive" that carries out effortful, limited-capacity processing will be discussed. In the following section the mechanisms of selective attention will be examined. The review will question where selective-attention effects occur in processing, and then a revised conception of the filtering mechanism will be offered. The subsequent section provides an analysis of certain derived components that can be omitted from the model; they appear to be compounds that emerge when the memory stores and the central executive operate in combination. The review culminates in a possible graphic representation of the processing system at a macroscopic level, guided by principles that will describe the limited objectives of the model. Finally, some alternative models that have been proposed by other investigators will be briefly assessed, and research issues will be addressed. In the Appendix, the major premises of the review are outlined, along with some of the key references supporting each premise.

Characteristics of Memory Storage

Broadbent's (1958) model was developed as an ordered series of memory stages. The multistore approach is supported by various findings suggesting that some experimental variables affect memories in one store but not in another. In the Broadbent (1958) model, information is first held in an unanalyzed form, in a sensory store of unlimited capacity. Some of this sensory information can be selected for further coding, and processed information is held in a limited-capacity, short-term store. This selected information is eventually filed in a permanent or long-term store, conceived as an extensive network of concepts composing the subjects' knowledge with some degree of organization. The multistore model was made more explicit by Atkinson and Shiffrin's (1968) emphasis on control processes that manage the transfer of information under the subject's effortful, voluntary control. For example, control processes operate to switch the focus of selective attention, maintain relevant information in the short-term store, and retrieve long-term information into the short-term store when necessary.

There are several fundamental issues about the mechanisms of memory storage left unresolved within this multistore model, for which recent research and theory is helpful. There is a problem in the presumed order of stores in the model. There is also a question of how short-term storage is to be operationally distinguished from long-term storage, on one side, and sensory storage, on the other. On the basis of this background, a clearer characterization of the stores can be presented.

Problem of the Order of Stores

Bower and Hilgard (1981) point out that the order of stores in the original multistore model seems "askew." Specifically, pattern recognition and coding processes must take place before information can be entered into the short-term store. These processes require contact with information in long-term memory, but in the multistore model, long-term memory is reached only later. Of course, the multistore model often is considered to include feedback loops from the long-term store to the short-term store, and/or a continuous flow of information from one store to the next (McClelland, 1979), but these qualifications of the traditional multistore model would not suffice to represent a perceptual process in which the information from sensory storage immediately makes contact with long-term storage.

A conceivable exception to the need for long-term information in order to create short-term storage is that innate feature detectors could deposit features directly into short-term storage. However, these feature detectors appear to be quickly tuned by experience. For example, infants' phonetic categories are influenced by the habitual speech environment (e.g., Werker & Tees, 1984). Similar tuning of feature detection occurs in the visual modality (e.g., Aslin, 1987). Thus, even if the infant is born with innate feature detectors, long-term memory soon becomes an integral part of the short-term storage process.

Another potential problem with the order of stores is that the contents of the subject's awareness are supposed to be in the short-term store (James, 1890; Klatzky, 1984; Stern, 1985). However, some information may be coded in long-term memory without first entering awareness (e.g., Balota, 1983; Dawson & Schell, 1982). If it is assumed that information must initially pass through each processing stage in a fixed serial order, then the store containing the information in awareness (i.e., the short-term store) must follow the initial contact with the long-term store, not precede it.

Anderson and Bower (1973) called for more specificity about what information is transferred from one store to another. For example, if the subject receives the stimulus word *dog* within a list, that word is already known. What is learned is that the word was presented in a particular serial position within a particular stimulus list; that is, the learning is of an episodic rather than semantic nature. This type of consideration suggested to Bower and Hilgard (1981) that "the sifting and selection among the input elements to determine what is already known and what is new would seem to require much more interaction between the two memory stores than what is envisioned [in the original multistore model]" (p. 432).

Short-Term Storage as an Active State

A sensible alternative to the original conception of stores is one in which short-term storage consists of the elements within the long-term store that are currently in a heightened state of activation. Norman (1968) incorporated this view into his model of memory and attention, and the idea was strengthened by findings suggesting that features and concepts in long-term memory can be automatically activated by incoming stimuli (LaBerge & Samuels, 1974; Morton, 1969). Shiffrin (1975, 1976) incorporated this concept into a revised processing model, with the short-term store depicted as a temporary file drawn from the long-term store.

Memory activation and awareness. Although the concept of short-term storage as an activated state is quite plausible, there is an important theoretical question that must eventually be resolved. Many researchers have suggested that the contents of awareness and of short-term storage are identical (see Stern, 1985, pp. 131–152). However, if there can be memory activation without awareness (i.e., subliminal perception), then one statement about short-term storage must be wrong. It could not include all activated memory and still be synonymous with awareness.

A possible resolution of this paradox is that activation must exceed a certain threshold level before it becomes part of awareness, and one might then define short-term storage as the set of all elements activated to the point of awareness. However, this definition of short-term storage could turn out to be problematic. There could be a continuum of awareness and, therefore, no clear division between superliminal and subliminal events. Macmillan's (1986) discussion of signal detection theory also leads to this suggestion.

As a measure of the subject's awareness of an item, one might use the time it takes to retrieve an item (see Roediger, Knight, & Kantowitz, 1977; Sternberg, 1966). Then one could determine if there is a discrete, quantal difference between two sets of reaction times (for items in awareness vs. out of awareness) rather than a continuum. However, if there is a continuum of reaction times, one might arbitrarily define a threshold level to be termed awareness. On the other hand, it would still be necessary to assess the unproven assumption that no factor other than the degree of memory activation influences the subject's awareness.

The concept of short-term storage is central to most issues in information processing, and it would not be wise to make its definition contingent upon the tricky concept of awareness. I will retain the definition of short-term storage as the sum of all activated information, and the question of what is in awareness will be viewed as an important but separate issue.

Memory activation and multiple stores. Given this view of short-term storage as an activated state, two additional questions about the nature of information transfer must be addressed. The first is how to interpret the data that have been used to demonstrate that short- and long-term stores are separate entities. It appears that some types of evidence on short-term storage reflect the properties of memory activation, whereas other types reflect the subset of activated memory that is in the focus of awareness. The second question is whether or not sensory- and short-term stores are distinct. The data suggest that the demarcation is real but should be drawn differently from most previous conceptions. There is a very brief sensory store that is distinct, but much of what has been termed sensory memory with a persistence of some seconds appears to be functionally similar to other activated features in memory.

Properties of Short-Term (Activated) Versus Long-Term Memory

Timing of memory activation. The alternative multistore models of processing may capture different aspects of the timing of information in short- and long-term storage. Broadbent's (1958) model correctly represents the persistence of information in each store. Information fades from sensory storage rapidly; it may persist longer in short-term storage; and it may be permanent in long-term storage. On the other hand, Shiffrin's (1975, 1976) processing diagrams, with short-term storage derived from long-term storage, instead represents the point at which each store first plays a role in processing. Information from sensory storage is coded using long-term memory information, and this leads to the formation of a short-term storage trace.

Neither model seems well-suited to represent the intricate timing of information processing that actually must occur. As an illustration for this chronology, the following processing steps seem likely: (a) The stimulus contacts information previously stored in long-term memory; (b) coding operations occur and an activated subset or short-term storage emerges; (c) new memories are entered into long-term storage (to some extent automatically and to some extent only with the assistance of attentive processing); and (d) the information fades from short-term storage. A chronology such as this might be represented in an hierarchical information-processing diagram in which time is depicted as a simple, linear dimension, so that the short- and long-term stores could be shown to be related and involved in processing concurrently.

Coding and control properties. At one time, many researchers believed that memory is coded phonetically in the short-term store and semantically in the long-term store (e.g., Baddeley, 1966a, 1966b). There was evidence of phonetic confusions among visually presented letters in short-term memory (Conrad, 1964) and evidence that, in the long term, subjects forget the exact wording of sentences and remember only the gist (Sachs, 1967). However, most researchers no longer take this to indicate a coding distinction between short- and long-term stores. Short-term storage can contain visual (Cooper & Shepard, 1973; Scarborough, 1972) or semantic (Shulman, 1972) information, and long-term memory can contain information about acoustic (e.g., voice) characteristics (see Cowan, 1984, p. 354).

A slightly different distinction that still seems valid is between memory control processes used with short- versus long-term storage. The few items in short-term (active) storage can be maintained by mentally scanning or rehearsing the entire set. The vast amount of information in long-term storage cannot be scanned, but the retrievability can be improved by forming associations between items. This implies that there must be reliance on control processes more closely associated with phonetic characteristics (e.g., rote rehearsal) for short-term storage versus semantic characteristics (e.g., memory elaboration) for long-term storage, but the association would be imperfect.

Storage capacity limits. In contrast to the vast store of long-term knowledge, short-term storage seems quite limited. The unresolved question is, "Limited in precisely what way"? Miller (1956) summarized evidence that subjects can retain at one time about seven items or "chunks." However, this type of statement is meaningless unless there is a clear way to identify a chunk. Simon (1974) suggested that a chunk can be determined when two equations using a common chunking parameter are known. (In addition to an equation for the number of chunks recalled in short-term memory, he noted that the study time per chunk in list learning is constant.) One could argue that the chunk has become dispensable in this approach; the relation between equations could be stated directly without reference to chunks. Fortunately, these points seem moot, because chunks usually correspond to easily identifiable units (syllables, words, etc.). Also, in cases of doubt, it would be possible to identify chunk boundaries in lists with an adaptation of the method that Johnson (1965) used to identify psychologically real phrase boundaries within sentences. He found that the conditional probability of correct recall (given that the previous item was recalled) decreased at phrase boundaries. Similarly, the memory list "IBMCIAFBIRCASOS," which consists entirely of meaningful 3-letter acronyms, should be recalled with sharp decreases in the conditional probability of correct recall after M, A, I, and A when chunking has occurred. There should be few within-acronym errors.

Estimates of short-term storage capacity may be inflated by contributions of the long-term store. To obtain pure estimates of short-term storage, some investigators (e.g., Glanzer & Razel, 1974; Watkins, 1974) have subtracted out the assumed contribution of long-term storage. The resulting estimate for adults is two or three items in short-term storage. Perhaps the number of activated memory items is limited to about seven, whereas the subset of these items in awareness and voluntary attention is limited to two or three.

Other researchers (Baddeley, Thomson, & Buchanan, 1975; Schweikert & Boruff, 1986) have suggested that verbal short-term memory is limited in the duration of storage as well as the number of items. When the list contains no organizing cues and rote rehearsal must be used, subjects appear able to recall as much as they can rehearse in 1.5–2.0 s. (This duration does not necessarily estimate simple memory decay, because the process of rehearsing or recalling one part of a sequence could interfere with memory for another part.) Thus, there appear to be constraints in both the number of items and the duration of pronounceable sequences in short-term storage. Although it is not clear how these two constraints work together, it might be possible to retain up to two or three chunks nonverbally while rehearsing other information (cf. Zhang & Simon, 1985). At least, some studies (Brooks, 1968; Scarborough, 1972) suggest that there are separate verbal and nonverbal components of short-term memory that can be used together.

Long- versus short-term storage: summary. How is one to reconcile the concept of short-term storage as an activated subset of long-term memory with the observable differences in the timing, control, and capacity properties of short- versus long-term memory? It appears that the distinct properties of short-term storage may be consequences of the types of processing that effectively keep memories in an active state (e.g., rehearsal), whereas the distinct properties of long-term storage may result from types of processing that are useful for efficient retrieval (e.g., semantic elaboration). Different capacity limits of short-term storage may result from the decay properties of activation, a possible limitation in how much of memory can be activated at once, and a limitation in what can be included in the focus of attention at one time.

Distinctions Between Sensory and Short-Term Stores

Overview. Much of what has been called sensory storage appears to be a special instance of short-term storage. There is evidence for the existence of two phases of sensory storage: a brief phase providing continued sensation for up to several hundred milliseconds and a second phase retaining more processed sensory information for some seconds. However, at least the second phase is one type of activated feature set or short-term storage. Direct comparisons of sensory and short-term stores will be presented, but first, an analysis of sensory storage is needed.

Perceptual coding and the concept of sensory storage. Although sensory storage can be loosely defined as a vivid memory for the qualities of sensation, it is necessary to use a more exact definition if sensory versus non-sensory memory forms are to be distinguished. It would seem that a memory must pass two criteria in order to be considered sensory in nature. First, the memory must not be directly translatable into the coding of another modality: it must be modality specific. For example, color and pitch are modality-specific dimensions, but the lexical identity of a word is not modality specific. Second, the memory must not be expressible simply in terms of an abstract category membership, regardless of whether or not the categories have verbal labels; it must be continuous information. For example, sensory memory for color must go beyond the category *blue-green* and beyond any other implicit color categories that may be contained within an individual's semantic memory system. It must include the specific shade of color within a color category. Similarly, to be considered sensory, the memory for a vowel sound must include vowel quality within phonemic categories and within any subphonemic categories that the individual may have learned to recognize. This definition presumably applies to both of the two phases of sensory storage that will be described.

The observation from physiological data that at least some feature detectors are arranged into discrete categories (e.g., orientation-specific columns of line detectors) need not imply that such feature detectors are incapable of preserving continuous, sensory information. The data both in vision (Hubel & Wiesel, 1963) and in hearing (Katsuki, 1961) suggest that feature detectors respond to each stimulus according to tuning curves rather than to absolute, all-or-none response patterns.

Two phases of sensory storage. The conventional description of sensory storage, to be found in many textbooks, is that there is a visual sensory store (iconic memory) lasting a few hundred milliseconds and an auditory sensory store ("echoic memory") lasting several seconds, with the duration of storage in other modalities not yet determined. There are good reasons to revise this description. Massaro (1972, 1975) and Cowan (1984, 1987a, 1987b) summarized considerable evidence that there are two phases of auditory sensory storage: an initial phase lasting several hundred milliseconds, in which there is an unanalyzed trace of the stimulus capable of extending its apparent duration (Efron, 1970a, 1970b, 1970c; Plomp, 1964), and a second phase lasting some seconds, in which there is partly analyzed information (e.g., coded speech features). This second phase of storage would be the one indexed by most measures of echoic memory, such as memory for unattended speech in dichotic listening (Broadbent, 1958), suffix effects (Crowder & Morton, 1969), and auditory partial report (Darwin, Turvey, & Crowder, 1972; Rostron, 1974). However, most of these techniques do not provide accurate estimates of the duration of storage, mainly because they do not eliminate forms of auditory interference and/or non-sensory coding during the period of presumed sensory memory decay.

When confounding factors are controlled, one can observe two classes of auditory experiment revealing memory traces of very different durations and storage properties (see Cowan, 1984). An experiment conducted by Kallman and Massaro (1979) serves as an interesting example. They presented three tones on each trial, in the order of *standard, [pause] target, mask* or *target, mask, [pause] standard.* The target-mask onset asynchrony was varied, and the time between the target and standard was fixed at 700 ms. Subjects were to say whether the target and standard were the same or different. Masking effects were obtained in either type of presentation, but the effects differed between the two. When the mask came second (i.e., between the target and standard), performance levels were lower, and there was an effect of the similarity between the standard and target independent of the masking interval. In contrast, when the mask occurred last, the similarity between the target and standard mattered only at short masking intervals. The interpretation was that a mask can interfere with both phases of sensory storage in different ways. The first phase can be overwritten whenever the mask is sufficiently close to the target, limiting the clarity of the target percept. However, whenever the mask intervenes between the target and standard, there is additional interference with the subject's memory of the target percept (i.e., interference with the second phase of auditory storage according to Cowan, 1984).

Estimates of the duration of the first, brief phase of auditory storage can be obtained from research by Efron (1970a, 1970b, 1970c) and Plomp (1964). Subjects in some of Efron's experiments were to estimate the time of onset or time of offset of a target tone by adjusting a marking stimulus (a contralateral noise burst or a visual flash) until it seemed to coincide with the target onset or offset in question. Onsets were estimated accurately, but the perceived point of offset for brief tones followed the true offset by up to almost 200 ms. Presumably, sensory storage extended the sensory persistence of the stimulus by this duration. Plomp (1964) found that two noise bursts in rapid succession often are perceived as one long burst, provided that the first burst is sufficiently intense in relation to the second and the interburst interval is sufficiently brief. The largest interburst interval at which this fusion can be obtained appears to be about 200 ms, presumably because sensory storage must traverse the interval for fusion to occur.

To obtain an estimate of the second phase of auditory storage, Cowan (1984) placed special importance on procedures in which the time between the memory item and the index of sensory memory was silent. For example, Eriksen and Johnson (1964) found that memory for near-threshold tones presented while the subject was silently reading remained above chance when a visual recall probe was presented 10 s after the tone. Cowan, Lichty, and Grove (1988) recently obtained similar results using syllable identification rather than tone detection. In experiments using a speech suffix to interfere with auditory memory for items in a spoken list, researchers previously believed that suffix effects could be obtained only if the suffix was presented within a few seconds of the spoken list. However, Watkins and Todres (1980) found that suffix interference could be obtained after a 20-s delay, provided that the delay was filled with a demanding task preventing the subject from rehearsing the memory list. The voice specificity of the spoken memory trace apparently decreases during this 20-s period (Balota & Duchek, 1986).

It may be more difficult to distinguish sensory from non-sensory short-term memory in the visual modality, because seemingly sensory spatial information actually might be coded as a combination of categorical features such as angles, line crossings, and regular geometrical forms. Nevertheless, there are good reasons to believe that there are two phases of sensory memory in the visual modality comparable to the auditory modality (see Massaro, 1975, chaps. 17 & 26). First, consistent with the original estimate of visual sensory storage obtained by Sperling (1960), Efron (1970a, 1970b, 1970c) obtained results that were very similar when the target stimulus was a light flash and when it was a tone. In both modalities, the first phase of sensory storage can extend the actual sensation for up to several hundred milliseconds.

There also is research suggesting that there is a longer and more processed phase of visual storage. Massaro (1975, pp. 528–529) presented two slightly different color patches on each trial and found that the ability to make same–different judgments decreased as the interstimulus interval increased from 0.5 s to 2 s (longer intervals were not tested).

Many other research findings also appear to be understood most easily with the concept of a visual sensory store lasting a number of seconds. For example, consider a procedure in which subjects were to compare either the names or the physical forms of letters presented visually in upper or lower case, with 0 to 2 s between letters (Posner, Boies, Eichelman, & Taylor, 1969). At short interstimulus intervals, performance was better for physical matches than for name matches. The advantage for physical matches decreased as the interstimulus interval increased, reflecting the decay of visual information. It is true that a random-dot pattern mask between the letters did not cause interference, which was taken as evidence that physical matches did not depend upon sensory information. However, the mask was quite dissimilar from the letters, and the amount of interference with visual information should depend upon the similarity of the target and mask if the visual effects are comparable to auditory phenomena such as the suffix effect (Morton, Crowder, & Prussin, 1971).

The physical-match condition in the Posner et al. (1969) study seems analogous to experiments using the AX procedure to index auditory memory. In this procedure, two brief sounds are presented with a variable interstimulus interval for a same-different judgment (Cowan & Morse, 1986; Crowder, 1982b; Pisoni, 1973). The effect of interstimulus delay in these experiments might estimate the decay of sensory information for the first stimulus (although a potential problem is that the second stimulus in a pair could interfere with memory for the first stimulus before the subject's judgment processes are complete). Parks, Kroll, Salzberg, and Parkinson (1972) obtained the visual physical-match advantage with 8 s between the stimuli, and the estimates of the decay of auditory memory in the AX procedure are in a similar range (see Cowan, 1984, Figures 1 and 4).

One clue that the visual store in Posner's task may be at least partly sensory in nature is that the temporal properties of the physical-match advantage depend upon the relative spatial locations of the two successive letters in a trial. Walker (1978) found that when the two letters were presented at the same locations, this advantage occurred across a much longer range of interstimulus intervals (between 6 and 15 s), whereas the advantage disappeared in less than 1 s when the second letter was presented slightly to one side. This may suggest that the visual comparison involves a sensory template-matching process requiring that successive stimuli be presented in the same location.

The location-specific nature of visual memory has been confirmed in several other procedures. Broadbent and Broadbent (1981) studied subjects' memory of visual patterns with the items either superimposed upon a common spatial location or presented to different locations. Also, covert rehearsal was suppressed. A strong recency effect was obtained only when the words were presented at a common location, presumably because each word interfered with the visual image of the previous word. The presentation rate (3 s per item) would be too slow for the results to be explained on the basis of Sperling's (1960) short-lived sensory trace.

In another relevant procedure, Phillips (1974) presented patterns formed from random arrays of filled squares, and subjects were to compare two patterns on each trial. The patterns were presented to the same location or with the second pattern shifted slightly (but still overlapping). Performance was found to be a decreasing function of the time between the two patterns only when the patterns occurred in the same location. Presumably, a visual sensory memory could not be used when the second pattern was shifted. Phillips found a delay effect across 9 s with patterns presented to the same location, but the effect of spatial location unfortunately was tested only for delays of up to 0.6 s. Phillips attributed the longer delay effect to visual short-term memory and would have to predict that this longer delay effect would occur with the stimuli in different spatial locations also. In contrast, the present approach leads to the prediction that the effect of spatial location might remain important throughout the delay period, but with less effect of delay for stimuli in different spatial locations.

The second phase of visual storage also could account for the advantage of a visual presentation modality in situations in which there is interference with auditory storage. For example, Scarborough (1972) modified the recall task of Peterson and Peterson (1959) to include visual as well as auditory presentation of the consonant trigrams. The advantage for visual presentation was maintained across a delay interval (filled with a backward counting task) of up to 18 s. An even longer period of visual sensory memory may have been observed in an experiment by Kroll, Parks, Parkinson, Bieber, and Johnson (1970). Subjects were to remember a single letter of the alphabet presented visually or auditorily while shadowing letters, and the advantage for the visual presentation modality was maintained across 25 s of shadowing.

There are two foreseeable objections to the hypothesis that there are comparable, short and long phases of sensory storage in the auditory and visual modalities. First, one might object that comparable visual and auditory procedures have yielded very different results. A partial report procedure with visual stimuli yields an estimate of storage of several hundred milliseconds (Sperling, 1960), whereas auditory partial report procedures yield estimates of at least several seconds (Darwin et al., 1972; Rostron, 1974). However, different phases of storage may have been indexed because of the poorer spatial acuity in audition and the consequent changes in procedure that were necessary. Sperling presented tachistoscopic arrays of 12 simultaneous items, presumably too great a number for perceptual analysis to occur. In contrast, in the auditory procedures, only three items were presented at a time, and considerable perceptual analysis might have been carried out automatically and in parallel. Thus, the auditory partial report advantage could be based on the retention of features held in the second, longer phase of sensory memory (also see Massaro, 1976).

A second possible objection to the proposed equivalence between visual and auditory sensory memory is that there is a well-documented auditory modality superiority in the recall of recent items (Penney, 1975). However, recent evidence (Glenberg & Swanson, 1986; Greene & Crowder, 1984) suggests that modality effects are not tied to auditory sensory storage. They can be obtained in stimulus series with long interference periods between items, and they can be obtained with lip-read rather than auditory speech information. The modality effects might result instead from superior encoding of spoken temporal sequences.

There also is evidence that the two phases of storage exist in the tactile senses. Forward and backward masking as well as temporal summation and fusion are obtained with interstimulus intervals of a fraction of a second, as in the auditory and visual modalities (Sherrick & Cholewiak, 1986), whereas the memory for tactile information persists for a number of seconds (Gilson & Baddeley, 1969; Pepper & Herman, 1970; Sullivan & Turvey, 1972).

It is unclear whether the duration of sensory storage differs somewhat across modalities, and it is also unclear whether the duration observed within a modality depends upon such factors as the subject's familiarity with the stimuli or their features. Nevertheless, there do seem to be two distinct forms of memory for sensation in each modality: one lasting less than 1 s, experienced as sensation, and a second lasting a number of seconds, experienced instead as a vivid recollection of the stimulus.

Although the existence of two phases of sensory storage might appear to complicate the effort to construct an information-processing model, actually the opposite is true. The second phase appears to be the retention of a stimulus that already has been partly processed automatically (e.g., into a set of feature values), and it would simply be a component of the short-term store. At least four beliefs have blocked this interpretation previously: (a) the belief that short-term storage lasts longer than sensory storage, (b) the belief that short-term storage is of limited capacity, whereas sensory storage is unlimited, (c) the belief that the contents of the short-term store are in awareness, whereas the contents of sensory memory need not be, and (d) the belief that short-term storage is coded, whereas sensory storage is uncoded. Each of these beliefs will be challenged below.

Duration of sensory versus short-term storage. The review of sensory memory suggested that the second phase lasts at least several seconds and quite likely 10 to 20 s. For the sake of comparison, the duration of short-term storage (i.e., of non-sensory memory activation) must be estimated. Theoretically, there are at least four requirements that must be met in order to obtain this estimate: (a) one must prevent or assess the contribution of sensory memory, (b) one must not interfere with the non-sensory memory that is being studied, (c) one must prevent rehearsal processes that would extend the period of activation, and (d) one must prevent or assess the effects of other factors that encourage attentive processing, such as the expectation that retention will be required. Various researchers have considered each of these problems, but no single study has controlled all of them. Nevertheless, estimates of short-term memory that have been obtained seem similar to the estimates of the second phase of sensory memory.

Two types of study are generally considered to provide estimates of the duration of short-term memory. In one type of study, Peterson and Peterson (1959) found that memory for auditorily presented letter triads decreased dramatically across an 18-s period filled with an attention-demanding task (counting backward by threes). In the other type of study, Glanzer and Cunitz (1966) and Postman and Phillips (1965) found that the recency effect in the recall of word lists decreased as the duration of a postlist counting task increased to 30 s. The subjects read the list items aloud in Glanzer's experiment and silently in Postman's experiment, but the results of both of these experiments were similar. All of these studies provide reasonably convergent estimates of the duration of short-term storage.

In order to assess the role of sensory memory in these procedures, it is necessary to manipulate the modality of the test stimuli and/or the distracting task. When a single modality is used, there is likely to be more interference with sensory memory than when the test stimuli and distracting task are presented in different modalities. Scarborough (1972) varied the presentation modality of the letters in the Peterson and Peterson task and found that the influence of modality was quite substantial (it accounted for roughly 50 percentage points in performance with a 9-s delay). On the other hand, Gardiner, Thompson, and Maskarinec (1974) manipulated the modality of both the word list and the distracting task in Glanzer's procedure, and they found effects of modality that amounted to only about 10 percentage points for the final list item (in contrast to an effect of delay across 30 s amounting to about 50 percentage points). In these experiments, the role of sensory memory is not absolutely clear, because the degree of physical similarity between the test stimuli and same-modality distractor tasks was not manipulated. Thus, more work is needed to assess the contributions of sensory and non-sensory short-term storage.

In the studies mentioned above, the distracting task also may have interfered with short-term memory material, and Reitman (1971) attempted to remedy this. She presented three words to be recalled on each trial, followed by a 15-s retention interval filled with a difficult signal detection task and then the recall period. In the critical trials, the subject's attention was devoted to a channel that remained silent. There was no evidence of memory decay, but in a sequel (Reitman, 1974) it was found that some subjects reported that they could rehearse the memory items despite the signal detection task. For subjects who truly did not rehearse, there was evidence of memory decay.

Watkins, Watkins, Craik, and Mazuryk (1973) devised a more powerful manipulation. They presented a set of words visually, followed by a series of tones. In the condition meant to prevent rehearsal of the memory list, subjects were to carry out a tone-recognition task. In the control task, subjects did not have to respond to the tones. There was no forgetting of the memory items during the delay interval in the control task, but there was marked memory decay across 20 s when tone recognition was required.

Muter (1980) focused on the possibility that subjects' knowledge of the task at the time of stimulus presentation could contribute to memory coding and influence the estimate of memory decay. He modified the Peterson and Peterson (1959) task so that recall of letters was required only in a small percentage of trials, thus making the recall task unexpected. Short-term memory for the letters in this situation decayed after only a few seconds of an interpolated activity (counting backward or reading words). However, these interpolated activities could have interfered with short-term memory. A totally suitable procedure to estimate the decay of short-term memory information presumably would be one in which both rehearsal and short-term memory interference are eliminated, as in the Watkins et al. (1973) study, expectations are controlled, as in the Muter (1980) study, and a meaningless, interfering item of varying physical similarity to the target items (e.g., a stimulus suffix) is used to assess the contribution of sensory memory.

Another important factor that may contribute to the observed estimate of short-term memory decay is proactive inhibition. Keppel and Underwood (1962) found that a memory decay function like the one observed by Peterson and Peterson (1959) does not materialize in the first trial. Instead, the amount of observable decay increases gradually across at least the first four or five trials. A likely explanation is that the material to be remembered is coded in both short- and long-term storage. If short-term storage has decayed, a search for the items in long-term storage still can take place, but proactive inhibition reduces the likelihood that this search will be successful. The conclusion that proactive inhibition occurs in long-term memory receives strong support from a list-recall experiment conducted by Craik and Birtwistle (1971), in which the primacy effect decreased across trials but the recency effect remained constant. Finally, in an experiment in which three spoken or printed letters to be remembered were followed by a shadowing task on each trial (Kroll, 1972), the most frequent source of errors was proactive inhibition (i.e., intrusions) from the stimuli in previous trials (except when auditory letter trigrams were followed by letters to be shadowed; then intrusions from shadowing were more frequent). In order to examine short-term storage factors, it may be necessary to exclude the trials in which the amount of proactive inhibition has not yet become stable.

There is another way to estimate the duration of short-term storage. Given that it is defined as the sum of activated memory elements, one might use as an estimate the decay of activation following a semantic priming stimulus. Examining the relevant studies, Anderson (1983, p. 104) suggested that estimates of the half-life of activation range from 400 ms to 4 s. Note that the duration of storage, defined as the longest duration at which statistically significant activation can be observed, would be several times longer than the half-life.

In summary, there is no evidence that would permit the conclusion that the duration of the second phase of sensory storage is shorter than the duration of short-term storage, in contrast to what is commonly believed. For both types of storage, estimates of persistence up to about 30 s have been obtained, although memory decay in both cases is most easily observable in the first few poststimulus seconds.

Capacity limits of sensory versus short-term storage. The second point of comparison is that sensory storage is said to be of unlimited capacity, whereas short-term storage is said to be limited in its capacity. However, the demonstrations of unlimited capacity in sensory storage involve only the first, brief phase (Sperling, 1960). Intuitively, an unlimited capacity for the longer phase of sensory storage seems unlikely. In the auditory modality, for example, the portion of the recency advantage clearly attributed to sensory memory is the last item of the list only (Balota & Engle, 1981; Greenberg & Engle, 1983). It is unlikely that a complex spatial array could be retained for some seconds in any modality, so the longer phase of sensory memory could be limited both spatially and temporally. It might be difficult to measure the limits precisely, but in any case there is no evidence of the unlimited capacity of sensory storage across some seconds.

Awareness in sensory versus short-term storage. The third point is that the contents of awareness are said to be in short-term storage (James, 1890; Klatzky, 1984; Stern, 1985), whereas subjects may be totally unaware of information in sensory storage (e.g., in the unattended channel during dichotic listening; Broadbent, 1958). However, if short-term storage consists of all activated elements within the long-term memory network, some of it may fall outside of awareness (see above).

One could consider awareness to result from effortful or limited-capacity processing (see Shiffrin & Schneider, 1977). These processes would focus as a "flashlight beam" upon a subset of the activated information, perhaps activating it further (cf. LaBerge & Samuels, 1974; Posner, 1978). In support of this concept, there is evidence that subjects are better able to verbally report items that have been processed effortfully (Fisk & Schneider, 1984; Tyler, Hertel, McCallum, & Ellis, 1979). Inasmuch as it seems possible to focus attention on information in (the second phase of) sensory storage just as one focuses on other stored items, both types of short-term information might operate in fundamentally the same way. Both would be memory in an activated state serving as a data base accessible to attentive processing.

Coding in sensory versus short-term storage. A closely related, final point is that the form of memory coding in the sensory versus short-term stores generally is assumed to differ. However, if coding were the only difference between the types of storage, there would be insufficient reason to believe that sensory and short-term storage are fundamentally separate mechanisms; the same dynamic mechanism could operate regardless of the specific coding. Using a reasoning process similar to this, Wickelgren (1973) argued that short- and long-term memory mechanisms should not be considered functionally distinct on the basis of different codes alone. Although short- and long-term stores might be considered functionally distinct for other reasons (see above), Wickelgren's rationale concerning coding should apply to the sensory versus short-term storage distinction also.

Actually, the coding of sensory and non-sensory short-term storage over some seconds does not differ as drastically as one might think. It is not the case that sensory information is unprocessed or uncoded. For example, Cowan and Morse (1986) found that the spoken vowels [i] (as in *beet*) and [I] (as in *bit*) are coded as points within an organized vowel space, with a systematic shift in the vowel location toward a less extreme point in the space, as well as a loss in precision, as the vowel memory decays. This systematic character of decay seems indicative of a coded memory trace. Yet, the coded memory was auditory rather than phonetic, inasmuch as subjects used it to discriminate among acoustically different vowels from the same phonetic category. Conversely, short-term memory material is not necessarily coded in terms of discrete categories. For example, subjects are able to imagine the rotation of a complex form continually in real time (e.g., Cooper & Shepard, 1973). This imagined rotation interacts with perceived aftereffects of rotation (Corballis & McLaren, 1982).

In sum, coding characteristics do not provide sufficient grounds to propose the functional separation between the second phase of sensory memory and short-term storage any more than do the concepts of duration, capacity, or access to awareness. Only the first phase of sensory storage seems separate, both because of its much shorter duration and because it alone is experienced as a continuation of sensory input.

Concept of Multifaceted Short-Term Store

If a variety of types of memory are to be grouped together theoretically into a single short-term store, it cannot be viewed as a simple store with a single-capacity limitation. One can retain more information when it is divided between two modalities (Henderson, 1972; Scarborough, 1972) or between two forms of coding (Brooks, 1968). However, the approach taken here is to view short-term storage as a complex entity with a capacity structure that may or may not include overall limitations as well as independent capacity limits for separate types of information.

The research suggesting that the second phase of sensory storage could be part of short-term storage does not imply that there are no sensory–modality-specific components of memory. Although the second phase of sensory memory interacts with other information in the processing system, one can still distinguish modality-specific components. For example, although recency and suffix effects can be obtained with either auditory or mouthed visual presentation of verbal items, the two types of presentations are influenced by different variables; for one, the auditory effect is restricted to vowel sounds, but the visual effect is not (Turner et al., 1987). Nevertheless, modality-specific components of memory could result from the temporary activation of elements within long-term storage, much as modality-free components do. The duration and conscious access to modality-specific and modality-free information in short-term storage could be comparable. Thus, the spectral, temporal, and spatial properties of sensation would be present as coded features in memory that behave in a way comparable to non-sensory features such as meaning and object categories. At least, this is the simplest hypothesis until evidence to the contrary is obtained. One might hypothesize that premotor and prespeech plans (see Baddeley, 1986; Cowan & Barron, 1987; Cowan, Braine, & Leavitt, 1985; Dell, 1986; Rosenbaum, Inhoff, & Gordon, 1984) also consist of activated memory elements.

Of course, initially, it is important not to overlook distinctions among sensory, abstract, and premotor memory storage or between types of coding such as verbal and spatial (cf. Crowder, 1982a). However, instead of focusing on the fractionation of short-term memory into separate types, the present article groups all forms together in order to highlight their possible similarities. All forms of short-term storage may consist of temporarily activated memory elements, and all may enter awareness when attentional processes are focused on them. It is these common features that appear to be most important when one is attempting to understand the overall organization of the processing system.

Central Processor or Executive

Now that three types of memory storage have been distinguished (a brief sensory store, a long-term store, and a short-term or activated-memory store), there is one additional basic component to be described in order to understand the processing system as it will appear in an overall model. This is the *central executive,* which is taken here to be equivalent to limited-capacity, control processes (Shiffrin & Schneider, 1977) or effortful processes (Kahneman, 1973). These terms all account for the observation that some information-processing operations are under the voluntary control of the subject (these involve the central executive), whereas other operations occur automatically (these do not involve the central executive). For the present purposes, any distinctions between the different terminologies can be ignored. The central executive presumably interacts with memory storage in important ways, which will be summarized after the central executive concept is clarified further.

Clarification of Central Executive Concept

The term central executive will be used to refer to all types of information processing, and all types of information transfer from one form of storage to another, that are under voluntary control. There is nothing magical about this view; volition can be observed, for example, through manipulations of task instructions and motivational variables.

It is important to guard against certain unwanted assumptions about the nature of the central executive. Foremost among these, one must avoid a homuncular notion in which the central executive would be viewed as capable of performing any information-processing task that could not be accounted for elsewhere in the model. On the other hand, it seems reasonable to permit the details of many of the central executive's operations to fall outside of the scope of this article. Without that freedom, interesting regularities in processing would be overlooked, and a general model of processing could not be formulated.

The central executive may be a conglomeration of different processes rather than a unified structure, but these processes at least are highly related. It is assumed that there is a limited pool of processing capacity that can be allocated to different information-transfer tasks. The amount of capacity needed for any particular task depends on the difficulty of the particular transfer operations being carried out. It is tentatively assumed that the central executive does not have domain-specific pools of capacity (see Broadbent, 1984). It is true that some pairs of effortful activities interfere with each other more than other pairs do, but the domain-specific interference could occur because of conflicting memory codes rather than conflicting executive operations.

Subjects presumably are aware of memory items that are being processed by the central executive, to an extent that depends on the relative effort invested in each item, whereas subjects presumably are unaware of information that is processed automatically. Reports from subjects who have performed the two types of processing confirm this view (see Fisk & Schneider, 1984; Klatzky, 1984; Tyler et al., 1979). According to the present use of terms, totally automatized procedures would become part of long-term memory instead of being central executive functions, except for the voluntary activation of the procedure. Baddeley's (1986) terminology seems to differ in this regard.

Information transfer operations of the central executive include at least the following: (a) the selection of information channels from short-term memory, (b) scanning short-term memory to select among items recently entered from the stimulus or from long-term memory, (c) the maintenance of information in short-term memory through various types of rehearsal, (d) long-term memory searches leading to the more elaborate storage of short-term memory information in long-term memory, and (e) problem-solving activities including principled long-term memory retrieval and a recombination of short-term memory units to form new associations.

Short-Term Storage With and Without Central Executive

Posner and Snyder (1975a, 1975b) proposed that there are two ways in which memory activation can occur, only one of which involves voluntary attention (and, presumably, involves the central executive). A concept in memory can be automatically activated by a stimulus, or attentive processes can be directed to the concept. Only the latter mechanism seems to lead to inhibition of nonselected categories (for supporting data see Balota, 1983; Neely, 1977). Posner and Snyder (1975b) stated that "once a subject invests his conscious attention in the processing of a stimulus, the benefit obtained from pathway activation is increased, and the benefit is accompanied by a widespread cost or inhibition in the ability of *any* other signals to rise to active attention" (their emphasis; p. 66).

If concepts "rise to active attention" by virtue of the total activation resulting from automatic and attentive sources together, then it might also be possible for a concept to reach awareness because its automatic activation alone surpasses a certain level, that is, automatic activation could redirect the focus of attention in the central executive or elicit an attention call. Schvaneveldt, Durso, and Mukherji (1982) also have suggested this, and a similar notion was used previously to explain the shift of attention when important information is presented in an unattended channel (Treisman, 1964a, 1964b). There may be reciprocal causal paths: automatic activation may direct attention, and attention may in turn influence the amount of memory activation.

An interesting implication of this view is that attention must be shared between external stimuli and memories activated through voluntary thought. (To a certain extent, one can become oblivious to outside events while concentrating.) In agreement with this implication, Farah (1985) found that the detection of a figure was aided by concurrent visualization of the same figure in the same spatial location but was impaired by visualization of a discrepant figure or location. In a shadowing experiment in which there were unexpected changes in the irrelevant message, Barr and Kapadnis (1986) found that the amount of disruption varied inversely with the difficulty of the primary, attended task. Thus, effortful activation of memory categories corresponding to relevant stimuli or concepts also improves the subject's resistance to the involuntary capturing of attention by irrelevant stimuli.

Long-Term Storage With and Without Central Executive

The vast research literature on how information is stored in long-term memory is outside of the scope of this paper, except for the aspects that clarify the interface between long-term storage and effortful versus automatic processing. In order to understand this interface, it is important to consider that many investigators have divided long-term storage into two or more categories, with distinctions such as episodic versus semantic memory, declarative or autobiographical versus procedural memory, and "knowing that" versus "knowing how" (for a review, see Tulving, 1985).

It is currently not possible to determine which distinction is most accurate, but the distinctions do seem to have something in common. They suggest that information can be retrieved voluntarily more often when effort and awareness are used during the storage process. This kind of storage is most likely to result in the kind of retrieval in which the subject consciously recalls the stimulus or event. On the other hand, it is possible to store some types of information even without effortful processing. In this case the subject may claim not to recall the event in question, but the memory will still affect his or her responses. For example, if a word was unattended at the time of its presentation, the subject might not recall having seen or heard the word but would still be more likely to produce that word in a subsequent task such as free association or spelling-fragment completion (Jacoby & Dallas, 1981; Kellogg, 1980; Tulving, 1985). Moreover, in amnesias caused by various neural traumas, the effortful-storage system often is severely impaired, whereas automatic storage remains intact (Squire & Cohen, 1984).

In the processing model that will be offered, two types of memory storage are represented separately within long-term memory. First, information that is processed effortfully and enters awareness is registered in an episodic storage system within the long-term store. Second, all incoming information, whether or not it enters awareness, contributes to a procedural storage system. This scheme leaves unresolved the origin and fate of the intermediate type of memory termed *semantic* (Tulving, 1985). It is likely that semantic memories often are formed through a combination of similar episodic traces; however, amnesics may learn a new semantic fact without recalling the episodes in which the new fact was learned (Jacoby & Dallas, 1981, p. 336). It may be that basic levels of semantic information (e.g., classes composed of stimuli that tend to co-occur) can be learned effortlessly, whereas more abstract levels of semantic information (e.g., a philosophical argument) can be learned only with effortful processing.

Mechanisms of Selective Attention

The existence of a limited-capacity attention system alone cannot explain which information is selectively attended to. There are involuntary shifts of attention, and some types of information can be attended to more easily than others. In light of these points, the automatic mechanisms of selective attention must be considered.

Overview

In the original formulation of a multistore model (Broadbent, 1958), the argument for the existence of separate stores was intricately tied to findings in selective attention. An attentional filter after the sensory store allowed a selected channel of information to pass to higher levels of processing, and it filtered out other channels. The subsequent literature on selective attention has focused primarily on whether the locus of filtering is actually this early in the processing system (i.e., preceding any perceptual analysis) or whether it is later in the system (i.e., following at least some perceptual analysis but preceding decision processes), as in the theories of Treisman (1960, 1964a, 1964b), Norman (1968), and Deutsch and Deutsch (1963).

In evaluating various concepts of selective attention, clear insights are heavily dependent upon an interrelated series of definitions and assumptions. Specifically, it is important to establish (a) a careful definition of an attentional filter, (b) assumptions about the chronology of the transfer of information from store to store, (c) a definition of perception, and (d) a justifiable set of assumptions about the mechanism of filtering or selection. A brief justification of these points will be followed by a more in-depth discussion of selective attention within the information-processing system.

A priori definition of the selective filter. The filter refers to a mechanism that, once set, can block the processing of some stimuli and allow the subject to further process other stimuli easily.

A filter must mean more than just a point of selectivity in processing; some investigators have pointed out the likelihood that selectivity occurs at many different levels of processing (Erdelyi, 1974; Johnston & Heinz, 1978). For example, one is usually selecting among stimuli even by directing one's gaze, and one is responding selectively to ideas in every conversation. However, these do not seem to involve a selective filter.

To show that a filter is operating, it must be demonstrated that processing in an attended channel proceeds just as effectively with or without the concurrent presentation of other, irrelevant stimulation that has been filtered out. For example, a person who is reading a newspaper and ignoring a television program is said to be filtering out the television program, provided that the newspaper could not be comprehended any more easily or quickly with the television turned off. To the extent that this type of definition breaks down, the attentional mechanism would not be a true filter, but it is useful to start with this distinction to emphasize that not all types of selective attention are comparable.

The filter and memory storage. It can be argued that proponents of a later filter have not found a convenient way to represent their positions graphically within the original multistore model. Immediate contact with information in long-term storage must be made in order for automatic perceptual processing to occur, but in the original model the long-term store was reached only after the short-term store, which was associated with awareness. Many late-filter theorists have underemphasized the possibility that shortcomings in the model's overall organization could block a coherent representation of selective attention. A late theory of selective attention is easier to represent when short-term storage is depicted as an active file drawn from long-term storage (cf. Norman, 1968). Competing channels of stimulus information would be perceptually analyzed through interaction with long-term storage, resulting in a set of activated codes. Particular sources of information would be activated to the level of awareness only insofar as they are pertinent to the task at hand or the subject's interests. Thus, a late filter would be placed after long-term storage and before whatever portion of short-term storage is taken to reflect awareness.

The filter and perception. Most researchers until recently have tended to contrast extreme views of the filter, with inadequate consideration of intermediate possibilities (perhaps because of the inherent limitations in what can be accomplished in a single study). Some investigators have described an extreme early view stating that no perceptual processing of unattended stimuli occurs (i.e., the model of Broadbent, 1958), and they have pitted this view against all others. On the other hand, other investigators have pitted against all others an extreme late view stating that the perceptual processing of stimuli is in no way affected by selective attention and that all attentional effects occur within the decision and response system (i.e., the model of Deutsch & Deutsch, 1963). One can hold the more moderate view that a partial, incomplete perceptual analysis of unattended stimuli takes place; many such intermediate views are possible (e.g., Erdelyi, 1974; Norman, 1968; Treisman, 1964a, 1964b).

However, the distinction between views of the filter depends on one's definition of perception (Erdelyi, 1974). For example, the extreme late-filter position states that selective attention does not influence perception at all, but the meaning of this view depends upon whether processes such as abstract stimulus coding and unconscious inferences about stimuli are counted as part of perception. This liberal definition of perception is implied by common usage. For example, the *American Heritage Dictionary* (Morris, 1976) defines perception as the act of becoming "aware of directly through any of the senses." If one accepts any definition of perception that includes more than the initial sensation, the data to be reviewed appear to rule out both extremes in favor of some intermediate-level filter.

Mechanism of filtering. It is also possible to propose changes in the assumptions about the characteristics of the selective-attention mechanism or filter. In the filtering device proposed by Broadbent (1958) and most subsequent researchers, any channel of information not specifically selected for further processing is automatically blocked (or at least attenuated), whereas information from selected channels is allowed to pass to higher processing levels unimpeded. The converse assumption is proposed here. Specifically, it is proposed that the subject rejects particular stimulus descriptions in the nonselected channels. The subject is assumed to habituate to nonselected channels and can remain habituated, provided that the unattended stimuli's physical characteristics remain relatively constant (e.g., no unpredictable change in intensity, location, spectral contour, or spatial distribution) and provided that there is no compelling signal value of the unattended stimuli (e.g., a word relevant to the attended input). The selection mechanism would consist of activation from the central executive that prevents habituation to the selected channel or channels. The benefits of this alternative description of filtering include an improved understanding of instances of penetration of the filter, a better unification of voluntary and involuntary attentional mechanisms, and greater compatibility of selective attention with a revised conception of information flow.

The discussion of selective attention will be divided into two main sections. (a) It is first necessary to form conclusions about the locus of attentional filtering. An intermediate-level filter will be proposed, although there are many unresolved details. (For more extensive reviews of selective attention, see Broadbent, 1982, 1984; Hillyard & Picton, 1979; Johnston & Dark, 1986; Kahneman & Treisman, 1984; and Posner & McLeod, 1982.) (b) On the basis of this review of the properties of selective attention, the evidence for a reconception of the selective-attention filter as an habituation mechanism will be discussed.

Locus of Selective Attention

Delineation of theoretical positions. In order to evaluate recent research, it will be necessary to keep in mind the circumstances upon which the original model of selective attention was formulated. Broadbent's (1958) conception of a selective filter relied largely upon selective-attention tasks such as dichotic listening. Subjects were easily able to comprehend one of several competing messages, provided that there were clear physical differences between the message channels (e.g., for sounds, pitch, and spatial location). Subjects seemed unaware of information presented to an unattended channel, but they were able to retrieve information presented to the unattended channel within the last few seconds. This suggested that information from all channels is held in a transient sensory store and that some kind of attentional filter prevents the information in unattended channels from being processed further.

The evidence that a filter permits attention to one channel has not been questioned, but the amount of processing that precedes filtering has been questioned a great deal. The early-filter hypothesis was contradicted by findings seeming to suggest that some of the unattended information in dichotic listening does reach the short- and long-term stores. Moray (1959) found that subjects sometimes detected their own names when these were presented in the unattended channel. Treisman (1960) switched the left and right channels during shadowing of prose and found that subjects sometimes incorrectly switched the ear of shadowing temporarily. (Usually, no more than one word from the unattended channel was repeated after each switch.) Treisman (1960, 1964a, 1964b) suggested that the attentional mechanism only attenuates incoming unattended messages rather than filtering them out completely. According to this view, stimuli that have lexical identities that are also sufficiently primed by contextual or personal significance do reach awareness.

Although the findings of Moray (1959) and Treisman (1960) are important in historical context and are usually cited as evidence of the failure of filtering, there are problems with these early studies. In Moray's experiment, the elicitation of attention when the subject's name was presented on the unattended channel occurred in only about a third of the trials, and it is possible that subjects were intermittently checking the supposedly unattended channel. In Treisman's experiment, one must bear in mind that when the unattended channel suddenly carried the coherent message stream, the attended channel simultaneously switched to an incoherent message. Subjects may have stopped attending selectively and picked up the next word from sensory memory of the unattended channel.[1]

On the basis of these studies and others, some (Allport, 1980; Deutsch & Deutsch, 1963) have suggested that there is only a late filter that selects among already perceived stimuli and that perceptual analysis runs to completion for all stimuli. Support for this approach includes the finding that unattended items influence the interpretation of attended items in selective listening (e.g., Lewis, 1970; MacKay, 1973) and that subliminally presented visual items cause semantic priming (e.g., Balota, 1983; Marcel, 1983a, 1983b). However, in an extensive review of this literature, Holender (1986) argued that there is no strong evidence ruling out confounding factors such as attention shifts.

Two qualifications of Holender's review should be noted. First, he was questioning whether semantic activation can occur without awareness of the information. The possibility that automatic semantic activation might occur and then recruit awareness was not relevant to Holender's thesis, but it is still consistent with the concept of a late filter. Second, the numerous commentaries following the review (e.g., Balota, 1986; Carr & Dagenbach, 1986; Fowler, 1986) provided additional support for the notion that automatic semantic activation of memory occurs in some situations.

Automatic semantic activation could be partial rather than total, however. One possible mechanism for partial activation was suggested by Johnston and Dark (1986) to explain results obtained by Bargh and Pietromonaco (1982): "It may be that a word exposed subliminally is not sufficient to activate a precise semantic representation of itself but can summate with other such words to activate a general schematic representation that embraces all of the words" (p. 62). The review of additional literature that is to follow supports an intermediate-level filter in which there is a partial, automatic semantic activation but not necessarily the complete recognition of unattended stimuli.

It is important to restate questions about the locus of the filter in terms of the specific analyses rather than in terms of perception in general. Selection is said to occur when none, some, or all of the perceptual process is complete, so one's hypothesis on the locus of filtering is dependent upon the definition of perception (see above). There appears to be a continuum of processing from sensation to cognition, and the subject's final identification of the stimulus depends not only upon sensation but also upon a progression of featural and semantic codes (cf. Posner, Snyder, & Davidson, 1980, p. 161) and even upon various levels of implicit inferences about the stimulus (Rock, 1986). Therefore, we must ask specifically which sensations, coding processes, or perceptual inferences are influenced by selective attention, and the review proceeds with this in mind.

Evidence on locus of filter. Perhaps the only point in processing where a precise dividing line can be established is in the distinction between sensation and other processes, which can be made on the basis of signal detection theory (Green & Swets, 1974). Sorkin, Pohlmann, and Gilliom (1973) asked whether selective attention enhances sensation. They presented a very quiet high (1400 Hz) tone, a low (630 Hz) tone, both, or neither on each trial, and subjects were to say which tone or tones were presented. The results suggested that simultaneous two-tone stimuli were detrimental to detection. However, Sperling and Dosher (1986) questioned the experimental logic on the grounds that the discriminability of the stimuli at threshold had not been established and response interference was not ruled out.

Moray (1975) more narrowly defined the test situations that could be taken as evidence for or against an influence of attention in the sensation process. He described a number of experiments in which intensity or frequency increments were presented dichotically or binaurally within streams of pure tones or other sounds. The conclusion was that "d' contingent on a contralateral correct rejection is not significantly different from d' in a dedicated mode" (i.e., a mode in which one channel is ignored; (p. 131). Because this was true of both channels, the result suggested that observers were able to monitor the channels in parallel. Detectability was affected when two signals actually were presented at once, but that finding could result from a resource limitation in the decision and response process (cf. Duncan, 1980). Moray pointed out that the same conclusions emerge when his type of analysis is applied to the data of Sorkin et al. (1973).

In the visual modality, some experiments have demonstrated that attentional cues can aid in stimulus detection (see Posner et al., 1980, for a review), but none of these experiments have included the type of contingent signal-detection measure used by Moray (1975). The experiments of Posner et al. (1980) used stimuli that were substantially above threshold and indicated that spatial attention cues can speed visual signal detection. However, this finding does not necessarily imply an effect of selective attention on signal detectability. For example, selective attention could instead activate the neural pathway that links a particular part of the visual field to the appropriate motor response. In summary, the available evidence on sensation (of which the auditory literature seems most relevant) suggests that

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[1] I am indebted to Neal Kroll for making these methodological points.

there is at least a very early stage of processing that is free of selectivity effects. More work in both modalities is needed.

Some investigators (e.g., Norman, 1968; Posner et al., 1980) appear to have adopted a fairly broad definition in which any coding processes contributing to the recognition or identification of stimuli are considered part of perception. (Many other investigators have not made their definitions this clear or explicit.) It is necessary to question how one would determine if attention affects the sensitivity (i.e., access) to various perceptual codes rather than just creating a bias toward certain codes. There is hope that signal detection theory could be used to clarify the effects of attention on these levels of processing beyond sensation.

The data suggest that there is an effect of selective attention on recognition sensitivity or *d'*. Treisman and Geffen (1967) presented target words embedded in sentences within both speech channels in a dichotic listening task. Subjects were to shadow one channel and, concurrently, make a tapping response whenever a target word occurred. It was possible to estimate false alarms by calculating how many words phonetically similar to the targets were presented on each channel. According to this analysis, the recognition *d'* was 4.2 for attended targets versus 1.8 for unattended targets. Moreover, when subjects did respond to unattended targets, the disruption of shadowing was much more severe than when subjects responded to attended targets. Moray and O'Brien (1967) obtained similar results in an experiment in which hits and false alarms could be measured more exactly. (Subjects listened for occasional letters within series of numbers, either on one channel or on both channels at the same time.) There was a continuum of recognition *d'* scores, with the highest scores for items in an attended channel, the lowest scores for items in an unattended channel, and intermediate scores in a divided-attention condition.

The role of attention in discriminative coding has been examined in another way in experiments in which an auditory target and a backward mask were presented concurrently with a visual perception task (Massaro & Kahn, 1973; Massaro & Warner, 1977). Target recognition appeared to improve less across masking intervals when a visual judgment also was required. However, the significant effects reported were main effects of the attention condition rather than an interaction of attention with the masking interval.

A lingering doubt about all of the effects of selective attention is that they might occur in memory rather than perception; that is, subjects might initially encode attended and unattended stimuli equally well, but they might translate the attended target into a response sooner while allowing information from an unattended or poorly attended channel to decay. However, if that were the case, one would expect shorter response latencies to targets in an attended channel than to unattended targets. Contradicting this expectation, Treisman and Geffen (1967) obtained nearly identical response latencies for targets in either channel.

There is a different group of experiments in which lower-level discriminations were required and no effects of selective attention on sensitivity were obtained. Lawson (1966) did not obtain an effect of selective attention in an experiment that was similar to that of Treisman and Geffen (1967), except that the targets were tones or pips that could be discriminated from the speech background with a relatively superficial perceptual analysis. Moore and Massaro (1973) found that performance in a backward recognition masking task was identical no matter whether subjects had to attend to two dimensions of a target sound (loudness and timbre) or to only one dimension. Taken together, the results suggest that there are some preliminary aspects of perceptual analysis that are not modified by selective attention and more advanced aspects that are modified.

There is converging evidence from other types of procedures, as well, for an intermediate-level theory rather than for an extreme late-filter theory. Kahneman and Treisman (1984) emphasized that late-filter theories do not have a convenient way to account for the initial facts that the filter was intended to accommodate, such as the relative ease of attending to one physical channel and the difficulty of attending to one semantic stream. Johnston and his colleagues have conducted research that also argues against a late filter. They have found that unattended information in dichotic listening receives less perceptual analysis than does attended information. For example, Johnston and Dark (1982) used an auditory task (detection of state names) to command attention to one or both channels and then presented a prime to either the right or the left channel. The auditory prime was relevant to a concurrent task in which subjects were to produce associations to visually presented words. The least priming effect was found with primes presented in an unattended channel, an intermediate effect was found with attention divided, and the greatest effect was found with primes in an attended channel. Johnston and Dark (1982, 1986) suggested that the perceptual analysis of unattended items is only partial and only of consequence when the semantic category of the unattended signal has been activated by prior information within the task (e.g., the relatedness of items on the relevant and irrelevant channels).

Research conducted by Eich (1984) provides explicit evidence for an intermediate-level filter. In the selective listening task that he used, the material presented to the unattended channel included word pairs in which the first word provided a context to interpret the second word (e.g., taxi—FARE). In a subsequent test session, subjects could not discriminate items that had been presented versus those that had not been presented in the unattended channel. Nevertheless, when asked to spell the ambiguous items, they more often used the presented versions, indicating that some perceptual analysis of these unattended items had taken place. This perceptual analysis apparently was partial rather than complete, though, because spelling scores were much higher in another condition in which subjects attended to the channel with homophones.

Recent psychophysiological evidence argues strongly against an extreme late-filter view. Hillyard, Hink, Schwent, and Picton (1973) found that event-related brain potentials to attended versus unattended stimuli diverged after only about 50 ms of processing. Hillyard and Munte (1984) found that selective attention to two visual attributes of each stimulus (location and color) affected evoked potentials in a temporal order that depended upon the relative discriminability of each attribute. Hackley and Graham (1987) ruled out a late filter in a task using a tone to modify the startle reflex, for which the neural circuitry is fairly well understood. The startle response was modified by selective attention to auditory stimuli presented in the left or right channels but not by selective attention to a medial channel composed of concurrent left and right stimulation. These results, along with the known neural innervation of the reflex, indicate that attention to a physically defined channel can enhance input to the reflex. It is still not clear exactly what behavioral aspects of information coding have been affected by attention in these psychophysiological experiments, however.

The recent evidence could lead to an interesting clash of convictions. Psychophysiological research appears to indicate that selective attention has an effect quite early in processing, whereas much of the cognitive research (e.g., work on semantic priming) appears to indicate that featural and semantic coding can occur automatically. However, these two positions could be compatible, given the weakness of the actual claims that most researchers have made. The psychophysiological researcher asks primarily if there are some early effects of attention, whereas the cognitive researcher asks primarily if certain types of coding can occur automatically. The observation of automatic processing adequate for a particular task need not imply that all of what one would term perception is carried out automatically. For example, a partial extraction of the visual features of a written word might lead to activation of semantic properties of the word even without featural information sufficient for the word's identification.

Results of Balota, Pollatsek, and Rayner (1985) clarify how this kind of automatic, partial extraction of features might work within reading. They monitored eye movements and fixation durations as subjects read text on a computer screen, and they made changes in certain target items between the times when these items were parafoveal and foveal (fixated). The parafoveal preview of each target was visually similar or dissimilar to the target when fixated, and the target was predictable or unpredictable in its sentence context. It was found that the visual similarity of the parafoveal preview to the target always facilitated reading speeds, but this parafoveal information was more facilitatory when the target word also was predictable. This suggests that the target word's lexical representation was activated from at least two convergent sources: automatic processing of parafoveal feature information and attentive processing of contextual constraints.

Eliminating the two extreme views of the filter is only a first step toward determining the level of the filter, and recent work has begun to venture further. Treisman and her colleagues (Treisman & Gelade, 1980; Treisman & Souther, 1986) suggested that features of individual visual forms are processed automatically, whereas specific feature combinations require attentive processes. However, the results of Prinzmetal, Presti, and Posner (1986) suggest that in some circumstances, individual item perception also can be enhanced by selective attention. Perhaps a general point applicable to these situations and others can be made more confidently. Voluntary attention allows perception to include contextual constraints that would not automatically be taken into account (e.g., the sentence context in word perception; see Stanovich & West, 1981).

If the feature–conjunction theory proves to be correct, it will be interesting to see how it applies to auditory and cross-modal stimuli. Results from a cross-modal Stroop task (Cowan & Barron, 1987) and from previous work on the effects of unattended speech (Salamé & Baddeley, 1982) suggest that subjects cannot easily attend to visual stimulation while ignoring all auditory stimulation. One intriguing possibility is that there may be multimodal objects formed from conjunctions of visual and auditory features. This is one way to understand the cross-modal effects of visually observed speech on the auditory perception of speech; for example, a visually observed [ga] can make an auditory [ba] sound like the syllable with an intermediate consonant, [da] (McGurk & MacDonald, 1976). It is not known if the cross-modal feature–combination process would occur as readily if the relevant features in one or both modalities were to be ignored during presentation.

Miller (1987) ruled out the particular intermediate-level filter in which stimuli are automatically processed only if their categories have been primed in advance (Treisman, 1960, 1964a), because semantic effects of unattended, unprimed stimuli were obtained. On each trial, subjects were to respond to a central letter (with a left versus right button press) and ignore flanking letters. Correlations between the flanking letters and the appropriate response facilitated subjects' performance without the subjects becoming aware of these correlations. As Miller pointed out, though, other intermediate-filter views have not been ruled out.

Norman (1968, p. 528) presumed that "nonattended inputs remain only partially interpreted." He suggested that items might be decoded to the morpheme or word level but that "the temporal integration of these basic units into more meaningful structures is not performed in the absence of selection." A slightly different possible filter would be one in which only a partial feature set results from the automatic encoding (perhaps containing some semantic as well as structural features). Miller's (1987) procedure could be adapted to address this issue. One question is whether the semantic effects of unattended, flanking letters depend upon automatic recognition of these letters. An alternative possibility is that features of letters enter directly into subjects' implicit knowledge of the stimulus correlations. If so, the magnitude of the effect should be smaller when the contrasting unattended items are visually similar. Also, unfamiliar or variable characters should be potent as unattended signals, provided that contrasting characters have distinct feature sets (e.g., rounded characters correlated with right button presses and angular characters correlated with left button presses). The theoretical basis for such effects would be partial, automatic coding, which is discussed next.

Partial coding and activation in a system with an intermediate-level filter. The existing data paradoxically suggest that selective attention has an effect on featural coding (e.g., Hillyard & Munte, 1984) and that selective attention sometimes is unnecessary for semantic coding (e.g., Miller, 1987). This paradox can be resolved if partial coding at a featural level permits coding on a semantic level to begin, as in a cascade model (McClelland, 1979). Both featural and semantic information exist within the long-term memory network and could be automatically activated. However, the activation of these codes could be enhanced further through voluntary attention.

The exact mechanism of the automatic activation of long-term memory is largely outside of the scope of this review; the data we will examine place few constraints upon it. Connectionist or parallel distributed processing models (e.g., McClelland & Rumelhart, 1985, 1986) provide one type of description for this activation process. According to this type of model, there is reciprocal activation between units at various levels of analysis. For example, automatic activation would be responsible for top–down processes in perception (e.g., Johnston & McClelland, 1974; Reicher, 1969; Warren, 1970), in which higher-level (e.g., lexical) context influences lower-level (e.g., phonemic or orthographic) decisions. The activation of higher-level categories would begin on the basis of partial feature information, and the category information would have reciprocal influences on the activation of feature codes.

In an alternative class of models, featural and contextual information are used as independent contributions to recognition. Massaro (1979) argued for this approach on the basis of an experiment in which subjects had to classify an ambiguous letter as *c* or *e*; lexical context did not alter subject's sensitivity. On the other hand, Samuel (1981) found that the sensitivity of auditory phoneme discrimination was influenced by the lexical context (but not by the broader sentence context). The findings of Connine and Clifton (1987) are consistent with this. All of these findings could be compatible if the memory network is connectionist only in a middle range, with influences of lexical units on lower-level unit activation (phonemes or letters) but no reciprocal activation flowing from higher levels (e.g., sentences) or to lower levels (e.g., features).

According to the present analysis, a connectionist network clearly would have to be supplemented by a central processor that could select a limited set of activated elements for further processing, such as the application of broad contextual (e.g., sentence) constraints. For an example of this type of hybrid model, see Schneider (1986) and Schneider and Detweiler (1987).

Implications of learned automaticity for attentional filtering. It is important to realize that the amount of automatic processing that occurs (i.e., the amount of processing before the filter) may depend upon the subject's familiarity with the stimulus materials. LaBerge and Samuels (1974) suggested that there are a variety of codes (e.g., for written language: feature, letter, spelling-pattern, and word codes) and that the links between levels of coding are first formed with the aid of limited-capacity processing and selective attention. Subsequent work has provided strong confirmation that processes that at first require attention become automatic with practice (Schneider & Fisk, 1982; Schneider & Shiffrin, 1977; Shiffrin & Dumais, 1981; Shiffrin & Schneider, 1977). Thus, it becomes necessary to refine the question concerning the level of the filter once more. For any particular perceptual process, one must ask (a) whether the process occurs automatically when the stimuli are unfamiliar and (b) to what extent the process is capable of becoming automatized with practice.

The experiments conducted by Schneider, Shiffrin, and others showed that subjects could identify letter targets among a set of numbers automatically and in parallel, without separate attention paid to individual characters. In contrast, distinctions between target and nontarget sets of characters from the same class had to be learned over several thousand trials before they became automatic. It is unclear whether automatization of simple featural distinctions would have to be learned at all (e.g., angular characters as distractors and a curvilinear character as the target), and it is unclear whether automatization of sufficiently complex or abstract forms of coding would ever take place (e.g., specific conjunctions of features as targets; bilateral symmetry of a character as the target). The existence of some lower and upper limits in the learning of automatization would be expected if there is an intermediate-level filter.

Intermediate-level filter within the processing system: summary. It is not yet possible to fully specify what aspects of perception proceed automatically and without voluntary attention (i.e., before the filter), but there are several conclusions that can be stated. First, although some of the distinctive features between classes of stimuli are detected automatically, not necessarily all of the important features are detected in this way. Second, the automatically detected features are sufficient for the recognition of the stimulus only in some circumstances (e.g., when there is a small, familiar response set). Third, the set of detected features (whether complete or incomplete) might lead to the automatic activation of some of the semantic characteristics of the stimuli.

Within the processing system in which short-term storage is conceived as an activated subset of memory, the parts of perception that proceed automatically are the coding processes that take place as the stimuli activate long-term memory. However, more complete perceptual interpretations occur when the stimulus information passes the filter. The central executive calls up additional relevant information and forms broader associations among the stimuli and between the stimuli and prior memories.

Habituation Hypothesis of Selective Attention

The habituation hypothesis is a reinterpretation of the filtering mechanism that, among other things, helps to address a fundamental and unresolved problem in attentional theory. Although it is easy to selectively attend to specific physical characteristics of input, it is also easy to detect a physical change in an unattended channel (Cherry, 1953). If the information from a channel is filtered out or attenuated on a physical basis, why should a physical change in that rejected channel be so easy to detect? The early-filter theory cannot explain this. On the other hand, a late-filter theory cannot readily explain why a semantic change is not also easily registered.

The habituation hypothesis, which can explain this phenomenon, turns out to be a variation of an intermediate-level filter theory; it requires that some perceptual analysis takes place automatically. The habituation account is based on the premise that the concept of filtering has been misleading. Although it has been supposed in past work that the selective mechanism accepts one physical channel of input, blocking all other physical channels, the converse may be true. The processing system may develop a physical description of the unwanted stimulation in memory, which would result in habituation to that stimulation and would inhibit the further processing of stimuli fitting that description. For example, in selective listening the system may develop a description of a particular male voice entering through an unattended channel.

Any physical change in the unattended stimulation would produce a mismatch with the description in memory, which would result in orienting (dishabituation) to this stimulus channel. In the selective-listening example offered above, a switch from a male to a female voice in the unattended channel would produce orienting to that voice.[2]

The orienting response is a conglomeration of neural, physiological, and behavioral changes that occur when the organism detects a novel or significant stimulus (Ohman, 1979; Posner & Rothbart, 1980; Rohrbaugh, 1984; Sokolov, 1963). For the present purposes, its most important features are (a) its tendency to direct the selective-attention mechanism to a stimulus modality, location, or channel in which the stimulus has changed recently and (b) habituation to stimuli that remain constant and do not prove to be of significance to the organism. Sokolov suggested that the primary mechanism behind the orienting response involves the subject's neural model of stimulation. It was assumed that continued presentation of a stimulus configuration leads to a neural model of the physical characteristics of the environment as the subject habituates to the stimulus. The incoming stimulation is compared to the already established neural model. If there is a discrepancy between the two, an orienting response to the discrepant stimulus is elicited.

More recent formulations (e.g., Ohman, 1979) include refinements of the neural-model concept. Subjects appear to form a set of implicit expectations about stimuli, and orienting occurs when these expectations are violated. It appears that the subject need not have explicit awareness of this process, because dishabituation of the orienting response can be obtained in subjects who are unaware of the eliciting stimulus change (Morse, Leavitt, Miller, & Romero, 1977).

The orienting response presumably works in combination with effortful, attentive processing to define the overall distribution of attention (Kahneman, 1973; Posner, 1980). There are three circumstances in which orienting may occur, drawing processing resources away from the prior voluntary focus of attention and causing the subject to reevaluate the priorities for attention: (a) when there is a change in the physical characteristics of unattended stimuli, such as the voice of the unattended message, (b) when there is a stimulus of long-standing significance to the subject, and (c) when the unattended channel contains information that has been primed by recent context. In each case, it is assumed that critical characteristics of an unattended signal have changed in relation to a neural model of the stimulation, resulting in a shift in attention. However, the evidence for (b) and (c) still is debatable (Holender, 1986).

Other theorists also have suggested that selective attention may involve active orienting to the attended stimulus (Posner, Cohen, Choate, Hockey, & Maylor, 1984) or inhibition of the unattended stimuli (Keele & Neill, 1978). However, these researchers did not fit their suggestions together into a model that resolves conflicts about the characteristics of selective attention.

Mackworth (1969) set a precedent for an habituation theory of selective attention in her analysis of vigilance tasks. Thus, she noted that the neural model of stimulation proposed by Sokolov (1963) "acts as a selective filter, inhibiting reaction to a stimulus which closely matches it" (p. 101). She also suggested that habituation "prevents a repetitive event from reaching awareness" (p. 102). However, Mackworth's conception of attention appears to be set within the original multistore conception of information flow. Thus, she stated that "unless attention is being paid to the incoming stimulus, nothing reaches the long-term storage" (p. 102).

Davies and Parasuraman (1982, p. 20) have presented reasons why the habituation hypothesis is not ideal to account for vigilance results. However, none of the reasons imply that the habituation hypothesis is inadequate to account for selective-attention mechanisms in fully alert subjects. Vigilance is likely to be a more complex situation that is affected by the subject's level of arousal, fatigue, and motivation, all factors that fall outside of the intended scope of the present article. It should be emphasized, then, that the present habituation hypothesis is intended to account for selective-attention constraints in alert subjects only.

An interesting consequence of the habituation model is that there is no absolute limit to the number of channels that can be monitored for critical changes in stimulation, provided that the total amount of information to be processed in these channels does not exceed the subject's processing capacity. This correctly predicts that multiple-channel detection or multiple-channel recognition from a very limited target set should not be impaired in relation to single-channel performance, provided that multiple simultaneous targets do not occur (Duncan, 1980; Moray, 1975; Schneider & Shiffrin, 1977; Shiffrin, 1975).

Several areas of research to be discussed provide further empirical support for the view that subjects attend selectively through habituation to the unattended stimuli. There is research indicating that prior habituation to stimuli that are to be presented in the unattended channel in selective attention facilitates performance. Conversely, presentation of a novel stimulus in an unattended channel results in orienting to that channel and disrupts task-relevant selective attention. Other research yields further insight into the mechanisms of habituation to irrelevant stimuli and supports the assumption that a neural model of the irrelevant stimulus and supports the assumption that a neural model of the irrelevant stimulus is constructed. Finally, there is evidence that the attentional focus is maintained through continuous effort; although the habituation–filtering process occurs automatically, active processes associated with the central executive are needed to prevent selected channels from habituating as nonselected channels do. The evidence of each type will be discussed in turn below.

Effects of habituation to unattended stimuli. Waters, McDonald, and Koresko (1977) sought evidence that habituation of the orienting response is "a gating mechanism subserving selective attention." The primary task was the solution of a set of arithmetic problems presented aurally in a male voice. Simultaneously in some conditions, random two-digit numbers were presented in a female voice as distractors. However, some subjects received prior presentations of the distracting stimuli. This distractor-habituated group oriented less to the distractors during the primary task performance than did the tone-habituated or nonhabituated control groups, and primary task performance also was highest in the distractor-habituated group. The effects occurred mainly during the first few (three to six) arithmetic problems. Lorch, Anderson, and Well (1984) and Lorch and Horn (1986) similarly obtained a facilitatory effect of preexposure to picture stimuli to be used as distractors in a speeded classification task.

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[2] I have recently learned of a similar view of habituation based on psychophysiological data (Woods, in press).

Effects of orienting to changes in unattended stimuli. Lorch et al. (1984) also conducted experiments in which the distractors were changed during the experiment. They obtained renewed disruption of the primary task. Several more complex predictions based on the theoretical description of habituation also were confirmed. Following the reintroduction of novel distractors, there was a reinstatement of interference by the original distractors and a disruption of no-distractor trials.

In selective listening with shadowing, a likely consequence of orienting to an item in an unattended channel is that the shadowing performance should be disrupted. Nielson and Sarason (1981) found that shadowing was disrupted by the presentation of a sexually explicit word in the unattended channel, especially for students high in anxiety. When Von Wright, Anderson, and Stenman (1975) paired items with shock and subsequently presented them as distractors in selective listening, there was continued physiological responding to these conditioned items, and shadowing performance tended to worsen with their repeated presentation. This point is important even if the data do not reflect subliminal perception.

Formation of a neural model. Kraut and his colleagues have provided evidence supporting the notion that subjects habituate to stimuli by constructing a neural model. Kraut and Smothergill (1978) proposed that familiarity to a stimulus typically engenders two processes: enhanced encoding of the stimulus (i.e., refinement of a neural model) and decreased alerting to the stimulus (i.e., habituation of the orienting response). They developed a situation in which these factors presumably worked in opposition. Subjects received habituation exposures to one of two colored circles to be used as response cues in a speeded task conducted either immediately or after a 15- or 30-min break. When the speeded task occurred immediately, responses were faster with novel cues, but when there was a break before the speeded task, responses were faster with familiar cues. Presumably, inhibition of alerting was the dominant factor at first, but this factor dissipated with time, and the additional encoding of the familiar stimulus became the critical factor.

The findings of Kraut (1976), with 6-year-old subjects, further support this view. He used a task in which a warning signal was followed by a cue to respond. Either stimulus could be familiar (i.e., habituated) or novel. In the presence of an unfamiliar warning signal, a familiar cue elicited the fastest performance, but without an unfamiliar warning signal, the unfamiliar cue worked better. The results suggested that an unfamiliar stimulus was preferable to alert the subject, whereas a well-encoded response cue was preferable, provided that the warning stimulus could alert the subject sufficiently.

The two-process account of habituation is useful in interpreting the results of a study conducted by Johnston (1978), who used a visual reaction time task to gauge the effort involved in an auditory selective-attention task with familiar or unfamiliar irrelevant materials. When there was only a semantic cue distinguishing the relevant and irrelevant materials, the reaction times increased with familiarity of the irrelevant auditory materials. This did not happen when there was a physical cue. In the former situation both streams of information would have to be examined effortfully, and prior encoding of the irrelevant information might make it seem somehow relevant. However, when there is a physical basis of stimulus selection, the habituation mechanism can screen out the irrelevant message, and the familiarity of this message would contribute to habituation.

Naatanen (1985, 1986) has obtained psychophysiological evidence that may reflect the formation of a neural model. There is a mismatch negativity (MMN) component of the evoked brain potential that emerges when there is a physical change within a series of stimuli; it is not elicited simply by a stimulus onset. The MMN occurs whether the subject is attending to the stimuli. Thus, it may reflect the neural response to a systematic discrepancy from the current neural model. Moreover, the MMN may clarify the link between habituation and sensory storage. The MMN lasts several hundred milliseconds after the discrepant stimulus, possibly concurrent with the first phase of sensory storage. Stimuli must be no further than several seconds apart for the MMN to be elicited, presumably because the longer type of sensory memory must remain sufficiently vivid for an automatic stimulus comparison to be made.

Active attentional focus. The aspect of selective attention complementary to involuntary orienting is effortful attention or active orienting to the selected channel. Posner et al. (1984) demonstrated that attention must be actively maintained. In a situation in which a visual reaction time probe was preceded by a directional cue, much less facilitation was observed when the cue remained valid for a small block of trials than when a different cue was presented after every trial. Thus, when sufficient effort is not exerted (i.e., with blocked presentation of cues), the subject presumably can habituate to the relevant channel or field in much the same way that he or she habituates to an irrelevant channel or field.

Finally, Hulstijn (1979) obtained psychophysiological results that illustrate the link between orienting and voluntary attention. Electrodermal indices of orienting were obtained for physical changes in auditory stimuli whether or not the subjects were attending to these physical traits, whereas orienting to semantic changes was obtained only when the semantic properties were attended to. The neural model of the stimulus may include primarily physical features plus whatever semantic features have been activated via the limited-capacity processing system. (It is not clear if orienting can be obtained for key unattended stimuli such as the subject's name, and if so, it is not clear if those responses are triggered through semantic or physical features of the key stimuli.)

Cautionary note. One must be careful not to overapply the perceptual habituation hypothesis to situations in which the stimuli may not actually be habituated. As an example of an experiment that only appears to exemplify habituation, Neill (1977) presented a series of Stroop trials (in which the subject is to name the color of ink forming a different color name) in which the distracting color name in one trial sometimes was the relevant color in the next trial (e.g., the word *red* in blue ink followed by *green* in red ink). With a vocal response, there was inhibition from the previous unattended item, and this might seem to be an example of habituation to the unattended items. However, when a manual response was used, there was facilitation rather than inhibition from the prior unattended item. It is clear that the inhibition occurred closer to the response system than to the perceptual system (also see Allport, Tipper, & Chmiel, 1985). In retrospect, one would not expect much perceptual habituation from a single presentation of the critical

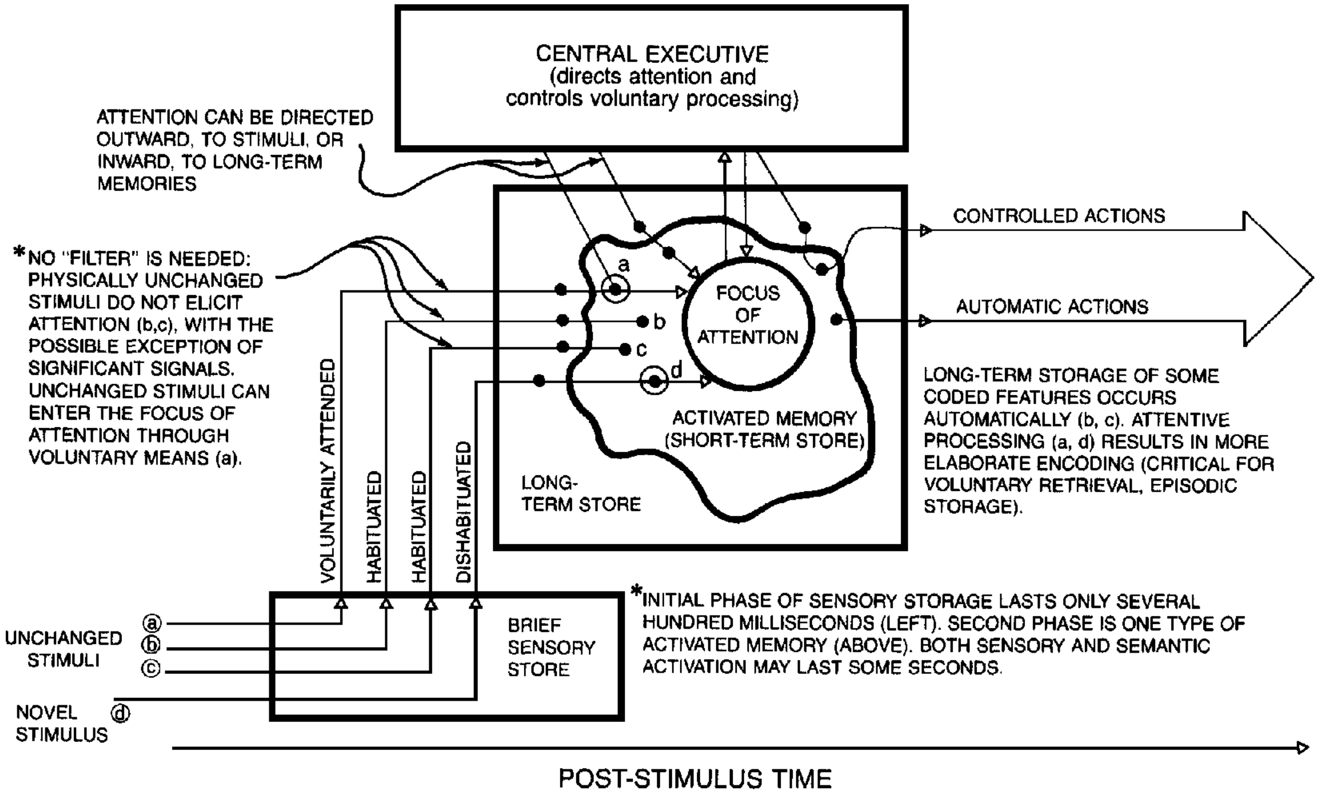

Figure 1. A revised model of the information-processing system. The time since stimulus reception is represented ordinally along the *x* axis. The components are arranged in real time, and stimulus information can be present in more than one component at the same time. Short-term storage is represented as an activated subset of long-term storage, and the focus of attention is represented as a subset of short-term storage. Habituated stimuli do not enter the focus of attention. The timing of involvement of the central executive in processing is flexible. The arrows represent the transfer of information from one form to another; these are discrete approximations to continuous processes that can occur in parallel or cascade. Pathways leading to awareness can come from three sources: changed stimuli for which there is dishabituation, items selected through effortful processing (whether of sensory origin or not), and the spontaneous activation of long-term memory information based on associations (not shown).

item. Instead, it might produce an active inhibition that would stem from central executive activity. This inhibition need not be limited to one response modality (Tipper & Driver, 1988; Tipper, MacQueen, & Brehaut, 1988).

Derived Components of Processing

The strength of the present conception of information processing depends upon the identification of a small repertoire of basic components: (a) sensory storage across several hundred milliseconds, (b) long-term memory, (c) a short-term store consisting of the activated subset of long-term memory, and (d) effortful, active processes or a central executive, which selects a subset of information in short-term storage as the focus of attention. Other possible components are considered to be derivatives of these basic components that need not be included in the model, although an accurate decomposition of these components is important.

A derived component generally corresponds to a mental function in which the central executive activates memory selectively and uses some of the activated memory to store temporary products of processing while further processing is completed. This combination of active and passive processes can be applied to various types of ability, and often an ability of this type is viewed holistically and referred to with a single term.

Two main examples of derived components occur within the working memory system as it is described by Baddeley (1986). Working memory is said to be composed of an articulatory loop and a visual scratch pad. Each of these types of memory could be decomposed into a passively held (automatic) and an active (effortful) component. Baddeley suggested that the articulatory loop consists of a passive, phonological store and a rehearsal process to continually reactivate that store. In the present framework, the phonological store is simply one instance of the short-term store, and rehearsal is one function of the central executive. The visual scratch pad would be similarly decomposed. Activated, short-term storage includes a visual component, and the central executive is able to activate images from long-term storage. Object manipulation such as mental rotation (Cooper & Shepard, 1973) would be accomplished when the central executive repeatedly reads the current contents of the activated visual store and computes (and activates) an image that differs from the current image by a small transformation.

Complex mental functions such as reasoning, learning, and problem solving presumably also rely upon passive storage and active processing together, but these types of function depend upon at least two major aspects of the cognitive system that fall outside of the scope of this review: (a) the structure of knowledge within long-term memory and (b) the structure and function of the central executive. Others (e.g., Anderson, 1983; McClelland & Rumelhart, 1986) have discussed these topics insightfully in ways that are compatible with the present approach. Consequently, further speculation here would be unproductive. I believe that the research on these complex mental processes could be used to generate important elaborations of the present model but that it does not call into question the basic structure of the model. (This view is clarified further in the section below on the work of Anderson, 1983.)

It is by concentrating on basic components and by ignoring both derived components and factions within the basic components that an overall model of processing was developed. That model and its aims will now be described.

Revised Graphic Representation of Processing

Guidelines for Modeling

A model obviously cannot resolve all of the issues in cognition. Consequently, it is necessary to state what the model is and is not trying to accomplish. This important point, unfortunately, has not been sufficiently emphasized within the field of information processing. A lack of specificity about the aims and assumptions of modeling could lead both to unwarranted criticisms and, conversely, to concealed inadequacies of the model. The present model attempts to adhere to the following guidelines.

Inclusiveness, accuracy, and nonexhaustiveness. The model should be inclusive: all of the abilities of the processing system should be included somewhere in the model. The model should also be accurate: the major subdivisions between components should correspond to the most important distinctions to be drawn between processing capabilities in the system. For example, subcomponents of the central processor may exist, but they are judged to be more similar to one another than they are to the storage structures. On the other hand, the model is not expected to be exhaustive. It need not include every distinction between different faculties in cognition. For one, future work might justify a division of the short-term store into separate sensory, abstract, and premotor components, but the model remains valid if the necessary modifications consist of a partitioning of the current components rather than restructuring of the system.

Conventions of graphic representation. In order to translate assumptions about processing into an easily understood form, the modeling diagram (Figure 1) is intended to represent the temporal sequence of storage and processing following the presentation of a stimulus. The x axis represents real time on an ordinal scale, and the processing path for any stimulus progresses unidirectionally from left to right. Each closed area in the model represents a functionally distinct processing component. Each is assumed also to have a distinct neural mechanism, although these mechanisms may be overlapping, spatiotemporal neural patterns.

Whenever it is assumed that information is processed in two or more components at the same time, these components overlap vertically (i.e., they have an x coordinate in common). Stores that are assumed to be subsets of other stores are represented that way: the focus of attention is a subset of activated memory, which in turn is a subset of long-term memory. Arrows represent the transfer of information from one component to another, in discrete approximations to transfers that can occur continually and in parallel.

Figure 1 differs from conventional multistore models, in which one had to move back and forth and/or left and right to trace the flow of information over time. The simple, linear representation of the figure safeguards against the inappropriate oversimplification in which the processing system is viewed as a machine with separate physical locations for each store.

Structure and Operation of Model

The structure and operation of the model depicted in Figure 1 reflects an attempt to coordinate the aspects of processing that have been reviewed throughout the article, using the guidelines for modeling that were summarized above.

Flow of information through components. When a stimulus is presented to the subject, it first enters a sensory store that preserves its physical properties (or, at least, many of them) for a period of up to several hundred milliseconds. During this time, information in the long-term store has started to become activated. This produces stimulus coding and short-term storage of the activated set of codes from long-term memory.

Activated codes corresponding to stimuli to which the subject has habituated remain in short-term storage but outside of awareness (e.g., items in the unattended channel in dichotic listening). However, stimuli that are sufficiently discrepant from the neural model of the prior stimulation, and possibly those that are of special significance to the subject, enter the focus of attention; in other words, they make an attention call to the central executive.

The central executive directs the process of voluntary attention, during which items are intentionally placed in the focus of awareness. The central executive also allows the subject to ruminate or think by voluntarily retrieving and activating some of the information from long-term storage. It is possible to have spontaneous thoughts (e.g., daydreams), as well, when the activation of certain items in long-term memory increases to some critical level without the assistance of the central executive.

Perception. The first phase of perception is one in which the long-term storage network is activated by the stimulus and converges upon a (not necessarily complete) set of featural and semantic categories. The second phase of perception is one in which information that has entered awareness is used to direct a more extensive search of long-term memory that will take into account additional aspects of the context in which the stimulus occurred.

Long-term storage. All perceptual and perceptual-motor experiences may modify a procedural long-term memory.[3] However, information that has entered awareness, either through deliberate selection by the central executive or through an attention call, also contributes to an episodic or "autobiographical" long-term trace. Procedural memory influences subsequent responding to new stimuli, but it cannot be deliberately retrieved as episodic memory can. Semantic memory is assumed to be intermediate between episodic and procedural encoding (Tulving, 1985) and might have multiple storage routes; this is still unclear.

Actions. Actions result from the activation of premotor and motor pathways in short-term storage. This information may have been activated through the central executive (voluntary actions), through spontaneous activity in the long-term storage network (involuntary actions), or through both together, which can result in errors of speech and action. Spontaneous activation of the memory network would occur according to principles that are not well understood (but see Dell, 1986; Rosenbaum et al., 1984).

Flexibility and variability in sequence of processing. The overlapping placement of processing components along the x axis, the ordinal scale of this axis, and the variety of transfers represented by arrows all are indicative of flexibility in the chronology and sequence of processing. Information enters an active, short-term state involuntarily, but the subject (whose volitions are represented in the central executive) can decide if and when to attend to it. The activation resulting from this attention can prolong the presence of the item in short-term storage.

Appraisal of Alternatives to the Present Approach

In the following section, various alternatives to the present approach will be discussed briefly and appraised, in order to clarify why the present approach may be preferable.

Wickelgren (1973): Single-Store Approach

Wickelgren (1973) reviewed the evidence allegedly in favor of the separation between short- and long-term memory. The alternative was the view that there is only one form of memory, with a decay function in which memory performance declines quickly at first (the short-term phase) and more slowly later (the long-term phase). He pointed out that differences in the memory functions for differently coded items (e.g., phonetic versus semantic) need not indicate two functionally distinct stores. On the basis of objections such as this one, most of the typically cited evidence for two stores was ruled out. A few types of evidence for two stores were tentatively accepted as valid, although in need of replication (e.g., the lack of paired associate interference in short-term retention only and the neuropathological dissociation of short- and long-term retention).

Actually, it is not clear if Wickelgren's single-store theory is the same as or different from the theory in which short-term storage consists of an activated subset of long-term storage. The findings that Wickelgren would take to be indicative of two stores could emerge even in the activated-subset version of the dual-store model, but it is not clear if the absence of these findings would rule out this model. Until an explicit version of the single-store model is developed, the classification of the present approach as a single-store versus dual-store model is unclear and would not fundamentally affect the way in which the mechanisms of storage are understood.

Levels of Processing: Another Single-Store Approach?

Craik and Lockhart (1972) advanced the notion that the retrievability of information depends upon the type of processing of the information; memory storage was seen as a by-product of the type of processing carried out, with better retention of materials processed at deeper levels. In the present context, we can bypass the subsequent controversy about the adequacy of the levels-of-processing approach (e.g., Baddeley, 1978; for a review, see Bower & Hilgard, 1981). What warrants emphasis here is that the levels approach could not account for the earlier data without some reference to a multistore concept. Specifically, Craik and Levy (1976) emphasized that the levels-of-processing approach does not negate the distinction between primary (i.e., short term) and secondary (i.e., long term) memory or between these types of memory and sensory memory. These are viewed as by-products of processing but are still important as storage substrates of the system. The stores would be obscured if both short- and long-term storage were not represented graphically in the model.

Shallice and Warrington (1970): Parallel-Stores Approach

Shallice and Warrington (1970) described a patient who had a greatly reduced short-term memory ability but normal long-term memory functioning. They noted that this is inconsistent with the multistore model in which information is passed to a long-term store via the short-term store, inasmuch as short-term storage failure would result in the transfer of degraded information to the long-term store. Their alternative solution was a system in which phonemic analyses are fed into a short-term store and semantic analyses are fed into a long-term store, with the two stores operating in parallel. They also allowed that these two types of inputs might be shared later through connections between the two stores.

However, I have discussed evidence that the short- and long-term stores cannot be distinguished on the basis of phonemic versus semantic content. The alternative view that was proposed is that the control processes associated with the two stores differ. The subject described by Shallice and Warrington may have had a deficiency in one or more of the control processes used to enhance short-term storage (e.g., covert articulation). This would also explain why the short-term memory deficit in this subject was later found to occur primarily for verbal items and why visually presented verbal items did not result in acoustic confusions as they do in normal subjects (Warrington & Shallice, 1972).

These factors suggest that the parallel-stores model is not necessary to account for the results. A parallel-stores model also is complex, because the memory activation resulting from input

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[3] Nissen (1987) did not observe learning in an unattended task, perhaps because the information to be learned was the sequential order of stimuli.

directly to long-term storage would not be considered part of short-term storage. The present model (Figure 1) is simpler.

Broadbent (1984): Flexible-Order Multistore Approach

Broadbent (1984) could be expected to agree with many of the criticisms of the original multistore model that have been described in the present article. Moreover, his Maltese cross model superficially resembles the present model (Figure 1). In his model there is a processing system that acts as a central switchboard controlling the transfer of information among four storage structures: (a) a sensory store, (b) a long-term associative store, (c) an abstract working memory, and (d) a motor output store. The processing system seems synonymous with the central executive or limited-capacity system of the present article. Broadbent's sensory store includes all forms of persistence of sensory information, which can last for several seconds or longer; as in most theoretical discussions, but unlike those of Kallman and Massaro (1979) or Cowan (1984), there is no distinction between two phases of memory for sensation. The long-term associative store is not fundamentally different than it was in the original multistore model. Broadbent's abstract working memory is depicted as a passive store for non-sensory and non-motor information; it does not include active processes applied to that store (e.g., a rehearsal process). Thus, it is identical to the structure that is often referred to as a short-term store. Finally, the motor output store is a buffer for motor programs.

One problem with this model is that there are insufficient restrictions on the sequence in which information can be transferred from store to store. There is no indication that a stimulus first enters a sensory store, then activates a portion of the long-term memory network, and then may enter awareness. Also, because short-term (working) memory is depicted as totally separate from the long-term store, the conception of short-term storage as an activated subset of long-term information is lost, and the older, separate-storage metaphor appears to be endorsed. This arrangement makes it seem as if the processing system could activate information within long-term storage to any extent that is desired without transferring this information to short-term storage.

Lastly, the Maltese cross model does not seem to explain selective attention in a clear and explicit manner. (This is not meant to imply that the single-store or parallel-store models do handle selective attention well; the descriptions of these models tend to ignore many of the problems of selective attention.) The filtering capabilities are placed within the processing system without a clear indication of what type of filter results. In order to accomplish this type of function, Broadbent (1984, p. 66) noted that "much storage of information over long term actually takes place within the processing system, and not in the arms of the cross at all." His justification is that different sets of information reside in these two components and that the distinction should not be obscured. However, the present model accomplishes filtering more simply with only one mechanism for long-term storage and an habituation mechanism of filtering.

Broadbent's (1984) model also indicates that abstract information can be used to modify the sensory trace of the stimulus. Although this notion may be valid for the second phase of sensory storage (e.g., to account for the interaction between lip-read speech information and memory for spoken items), it is completely invalid for the first phase of sensory storage lasting only several hundred milliseconds. That is one reason why it seems important to make the distinction between the two types of sensory store and to consider the possibility that the second phase is functionally no different from other short-term memory information. The possibility that premotor plans are part of a multifaceted short-term store, with activation and decay characteristics similar to sensory or abstract information, also should be considered.

Anderson (1983): Computer Model of Memory Storage and Activation

Anderson (1983) has formulated an "ACT*" (adaptive control of thought) model of the information-processing system that appears to be complementary to the present approach. ACT* includes a declarative memory, a production memory, and a working memory. The working memory consists of the activated memory nodes from either declarative or production memory, making it similar to the short-term store of the present model (and different from the working memory of Baddeley, 1986). The details of production memory allow a variety of perceptual encoding processes, problem-solving operations, and performance functions to be carried out in a determinate manner (generally through pattern-matching procedures), guided by declarative knowledge. This production memory appears to be a detailed, plausible model of how the central executive could operate in some situations (although it also appears to include automatized procedures, unlike the central executive as I define it).

Anderson assumes that a large amount of memory information can be in an active state at one time, although this activated memory decays. He also assumes that the current goal element derived from the production memory is capable of maintaining or prolonging the active state of a very limited amount of information. This limited amount of information appears to correspond to the focus of attention in the present model. ACT* probably also could address the issue of long-term memory coding for items in awareness versus those out of awareness. Specifically, the linking of consecutive events to a common goal structure could account for the preservation of episodic memory for items in the focus of attention. If so, it might be predicted that episodic memory for moments in which there were goal changes would tend to be incoherent.

Thus, the ACT* model seems consistent with the present model and provides many useful elaborations of it. On the other hand, two important issues of processing were not specifically addressed by Anderson. First, the nature of sensory storage was not addressed. The longer phase of sensory storage as a set of modality-specific feature values is quite consistent with ACT*, but the brief, literal phase of sensory storage was not described. Second, the automatic selective-attention mechanism was not discussed. There is apparently nothing in ACT* that could be used to predict that subjects can attend to physical channels more easily than semantic channels, and there is nothing to explain why changes in unattended channels are noticed. It seems likely, though, that the phases of sensory storage and an habituation mechanism of selective attention could be added to ACT* without difficulty.

Humans live in a busy world filled with many irrelevant and/or physically complex stimuli, whereas computer models of cognition usually have the luxury of receiving a restricted set of relevant, partly coded stimuli. This may account for the apparent lack of interest in sensory memory and selective attention in Anderson's model. The same point may apply to other computer models of cognition, such as the model described by Laird, Rosenbloom, and Newell (1986).

Research Issues

The intent of this final section is to point out some types of research that might be generated by the present approach. Research is needed both to confirm predictions of the model and to further clarify particular processes. Research issues will be discussed for four aspects of the model: (a) the conception of sensory storage in which there is a brief, literal phase and a second, longer phase that operates in a manner similar to the rest of activated memory, (b) the distinction between short-term storage as an activated memory set and the focus of attention as the subset that is in awareness, (c) the conception of selective attention based on habituation and the attention-directing capability of the central executive, and (d) the analysis of working memory systems as derived from automatic activation and central executive processes working together. Research issues in these areas will be discussed in turn.

Short and Long Sensory Stores

The hypothesis that there are two phases of sensory storage, functionally similar in all modalities, is supported by a great deal of circumstantial evidence but very little research in which the two stores are demonstrated within the same experiment. The best example of a study demonstrating two stores is the Kallman and Massaro (1979) study in tone masking, and it is important for a similar experiment to be conducted in the visual modality. This would permit a comparison between the present approach and the common belief that visual storage is simply much shorter than auditory storage.

In a comparison of these approaches, it is also important to determine why modality differences in recall are obtained. The hypothesis that spatial coding is superior in vision and temporal coding in audition must be further investigated. Also, it is important to examine the ways in which spatial and temporal coding limitations have invalidated comparisons between the modalities (Glenberg & Swanson, 1986).

If there is a longer visual trace, similar to the longer phase of auditory storage, it may be possible to observe memory for visual stimuli that are automatically perceived but outside of the focus of attention. Attempts to develop visual analogs to dichotic listening have been made (Fitzgerald & Broadbent, 1985; Wolford & Morrison, 1980), but there has been no attempt to measure the rate of decay of visual information in these procedures. Moreover, given the problem of retroactive interference, it might be preferable to develop for this purpose a visual analogue to the Eriksen and Johnson (1964) unattended-tone procedure.

In the present review, it was proposed that the second phase of sensory storage actually is just one type of activated or short-term storage. This concept might be investigated by manipulating sensory characteristics of the stimuli in priming studies. A prime should activate sensory features in memory that are useful for the recognition of a stimulus that shares some of these sensory features.

An unanswered question in the present approach is whether the central executive can operate upon all activated memory elements (including the longer phase of sensory memory) in the same way. Can subjects keep sensory information active longer by attending to the stimuli? This is not clear. It could be examined in two-stimulus comparison experiments in which the first stimulus is either attended or unattended at the time of presentation.

It is not clear exactly how the central executive reactivates an item in memory. Is it enough to attend to the item, or must domain-specific processes (e.g., verbal rehearsal or mental imagery) be carried out? Further, to return to a question hinted at above, can sensory features be rehearsed? In one relevant study, Massaro (1970) found that subjects in a two-tone comparison task performed worse, not better, when instructed to hum the first tone in the intertone interval. However, the humming may have been inaccurate or poorly suited to pure-tone recall. Perhaps subjects have to be able to imagine producing the stimuli in order to rehearse them and should have been instructed to imagine whistling rather than humming aloud.

Short-Term Activation and Focus of Attention

Whereas the memory activation concept has been validated in numerous studies (e.g., of semantic priming and fact retrieval), we still must develop a way to operationalize the concept of a focus of attention. Additionally, we must determine the separate capacity limitations of both memory activation and the focus of attention. It is likely that empirical advances in these areas will be interdependent.

For example, in order to empirically confirm the existence of a focus of attention, it may be necessary to demonstrate its capacity limit. It was suggested above that the time needed to mentally access information may be shorter for items inside of the focus of attention. Perhaps the reaction-time measure could usefully be combined with attention-focusing instructions. Subjects in a memory-scanning procedure (Sternberg, 1966), after committing to memory a seven-character set, might be instructed to focus on one or several of the items within this set. The reaction times for items in focus should be less than those for other items in the set, but the maximal increase should be obtained only when the subject is instructed to focus on few enough items to fit in the focus. An alternative possible outcome is that rather than a discrete capacity limit for the focus of attention, the beam of attention can be focused or diffused across any number of activated items.

There is little direct information on how much of the long-term memory network can be activated at once. This might be investigated in research with multiple priming stimuli presented in a single trial.

Selective Attention and Habituation

Much of the work needed to confirm the habituation theory of selective attention would consist of replications and extensions of work that has already been done, because there are a number of important effects that have been demonstrated in one or two studies only (e.g., the effects obtained by Waters et al., 1977).

However, there is a straightforward prediction of the habituation theory of selective attention that has not been explored. Specifically, the conditions eliciting attention to an unattended channel should be similar to the conditions causing physiological dishabituation, which have been examined for a variety of species and circumstances (see above). One relevant principle is that the amount of habituation exposure needed before a recovery can take place should depend upon the complexity of the habituating stimulus, because it takes more time for a neural model to be generated for a complex stimulus.

I am investigating this prediction currently by using a selective listening procedure. The habituating sequence in the unattended channel consists of a single syllable of speech (e.g., *ba, ba, ba*) or several syllables in alternation (e.g., *ba, ga, pa, ba, ga, pa*). The expectation is that the compound syllabic stream must be presented for a longer time before the subject will be in a position to notice the introduction of a novel syllable (e.g., *da*). Preliminary data confirm that subjects can detect phonetic changes in unattended stimuli provided that there is a simple, stable habituating stimulus. This would not have been predicted on the basis of earlier conceptions of the selective-listening process.

More work is needed also to determine the factors that contribute to habituation. Although the neural model presumably necessary for habituation might be formed partly or entirely on the basis of an automatic perceptual analysis, it seems likely that processing directed by a central executive can speed up or enhance the formation of a neural model. If so, an initial, attentive familiarization to the sequence to be presented in the unattended channel should not only make it easier for the subject to maintain selective attention, as Waters et al. (1977) found, but should also make it easier to detect subtle changes in the unattended channel (i.e., discrepancies from the neural model). An additional unresolved question is whether there is a long-term counterpart to habituation, which would help humans to ignore stimuli that remain relatively unimportant and occur frequently but intermittently.

The present model naturally leaves open the controversial but often researched question (see Holender, 1986) of exactly how much semantic processing is included in the automatic phase of perceptual analysis. Presumably, any automatically encoded semantic features would become part of the neural model of the unattended stimulus. Finally, the suggestion that significant stimuli (such as one's own name) elicit attention also must be examined further. The often cited experiment of Moray (1959) should be repeated with additional controls. For example, one might monitor the rate and accuracy of shadowing in order to determine whether subjects stray from the shadowing task shortly before noticing their names on the unattended channel. Even if the automatic detection of one's own name is demonstrated, it must be determined whether this is based on semantic or phonetic properties of the name.

Working Memory Systems as Derived Components

There is a trait of working memory that at first appears to be at odds with the present analysis of working memory as a derived component of processing. Specifically, subjects remember only about as much as they can rehearse in about 2 s (Baddeley et al., 1975; Schweikert & Boruff, 1986; Zhang & Simon, 1985). According to the present approach, subjects retain a list of verbal items by using rehearsal to renew the activation of the sequence of items. For complete recall in a memory span task, one must be able to reactivate all of the items and return to the first item before it has decayed. Therefore, one might expect that subjects could remember as much as they could rehearse in the time it takes short-term memory to decay. On the basis of estimates of short-term memory decay (see above), one might expect a rehearsal-loop time longer than 2 s (e.g., perhaps 10 s).

There are several reasons why the 2-s rehearsal-loop time may not be a valid estimate of the duration of short-term memory decay. First, memory span may be reduced by output interference (both sensory and abstract) during the recall phase. Second, there may be interference within the rehearsal phase; it may not be possible to rehearse one item without interfering to some extent with the memory for other items in the sequence. A different possibility is that activation for any one item decays faster when other items also are activated. I will leave as an unanswered question, which I have not resolved to my own satisfaction, how to best empirically investigate these three alternatives.

Conclusion

The present review has suggested that an information-processing model with sensory, short-term, and long-term memory stores is feasible and useful, provided that several fundamental changes are made from the assumptions of the conventional models. (a) Sensory storage may be functionally distinct from other forms of short-term storage only in the first few hundred milliseconds. For example, it may only be within this period that the memory cannot be modified by or combined with other, nonsensory information. It is only the brief form of sensory storage that seems to extend the duration of effective stimulation. (b) As Norman (1968) and others have pointed out, short-term storage should be viewed as an activated subset of long-term memory. Not all of the activated information automatically enters awareness, but the processing system that is identified with awareness (the limited-capacity system or central executive) may use activated information as an easily accessible data base. (c) Selective attention involves habituation rather than filtering as it is usually conceived. It is particular unchanged stimulus descriptions that are rejected from further processing rather than entire physical channels. This implies that some perceptual processing occurs independently of attentive processes, although attention does result in a much more elaborate stimulus encoding.

These points were combined in a model of processing (Figure 1) in which vertical stacking and set–subset relations were used to represent the functioning of components partly in parallel or cascade rather than in a strictly serial fashion. Importantly, assumptions that have gone into the model have placed mutual constraints on one another. The concept of two sensory stores has made possible the concept that the longer one contains feature information; the concept of short-term storage as an activated subset of long-term memory that includes sensory and semantic feature coding has made possible the concept of habituation to the stimuli in unattended channels; and the habituation hypothesis eliminates the need to propose either an early or a late filter, both of which seem discrepant with the memory and attention literature.

One might object that the model combines disparate processes in an overly simplistic fashion. Many different types of information were simply said to coexist within short-term storage, and many types of processes were included in the central executive. These simplifications were not meant to imply that further processing distinctions are unimportant. However, the intent was to construct a model that captures the organization of the system by combining specific mechanisms into more general components.

A fundamental challenge to the information-processing approach might question the attempt to represent the flow of information in a schematic and linear fashion. I hope it is now clear that, in doing so, we would lose considerable understanding of the temporal sequence of events that ensues when a human being perceives and responds to stimulation.

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Appendix

Major Premises of the Review and Some Key References

Shortcoming of Original Multistore Model

In the original model of information processing, information was transferred serially from sensory to short-term and then to long-term storage (Broadbent, 1958). However, short-term storage requires prior long-term information (Bower & Hilgard, 1981).

Alternative Conception of Short-Term Storage

Short-term storage can be viewed as the portion of long-term memory currently in an active state (Morton, 1969; Norman, 1968).

Distinctions Between Stores

1. Short-term storage differs from long-term storage in the timing of these stores in processing (Broadbent, 1958; Shiffrin, 1975, 1976), the different control processes typically used with short- versus long-term storage (Atkinson & Shiffrin, 1968; Shiffrin & Schneider, 1977), and the limited capacity of short-term storage (Miller, 1956; Watkins, 1974; Zhang & Simon, 1985).
2. The distinction between short-term storage and sensory storage is not what most investigators have supposed. There are two phases of sensory storage: a brief phase extending the duration of sensation for several hundred milliseconds and a second phase in which more processed sensory codes are saved for some seconds (Cowan, 1984, 1987a, 1987b; Kallman & Massaro, 1979). The first phase is distinct because of its unlimited capacity (Sperling, 1960) and afterimage quality (Efron, 1970a, 1970b, 1970c). The second phase may be just one instance of short-term storage.

Central Processor or Executive

The central processor or executive is defined here as a collection of all effortful processes (Kahneman, 1973) or limited-capacity, controlled processes (Shiffrin & Schneider, 1977). There is no implication that all processes in the central executive form a unitary entity. Anderson (1983) has analyzed many of the processes that would be included here.

Memory Storage With and Without Central Executive

Memory can be addressed and altered in two ways: automatically or through the intervention of central executive processes (LaBerge & Samuels, 1974; Neely, 1977; Posner, 1978). Subjects are not necessarily aware of all items in activated or short-term storage; they are only aware of those items processed by the central executive (Fisk & Schneider, 1984; Tyler et al., 1979), that is, the focus of attention. This view is supported by reports of the automatic semantic activation of memory (Balota, 1983; Dawson & Schell, 1982; Marcel, 1983a, 1983b; Miller, 1987). The central executive would use information in short-term storage as a readily accessible data base (Roediger et al., 1977; Sternberg, 1966).

Long-term learning during effortful processing and awareness yields memories that can be deliberately recalled; episodic learning is of this type. In the absence of effortful processing, there is still learning that influences responding to subsequent stimuli; procedural learning may occur (Jacoby & Dallas, 1981; Squire & Cohen, 1984; Tulving, 1985).

Locus of Attentional Filtering Device

Research on selective attention has contrasted an early-filter theory, in which rejected input is blocked before perception (Broadbent, 1958), with a late-filter theory, in which all stimuli are perceived but some stimuli are selected for further processing and responding (Deutsch & Deutsch, 1963). Intermediate views are possible (Erdelyi, 1974; Norman, 1968; Treisman, 1964a, 1964b), and the data suggest that some intermediate view is correct (Eich, 1984; Hillyard & Munte, 1984; Moray & O'Brien, 1967; Treisman & Geffen, 1967).

For unattended stimuli, a partial set of physical features that are extracted automatically might be sufficient for some semantic features also to emerge (McClelland & Rumelhart, 1986).

Habituation as Mechanism of Filtering

The filter theories previously discussed do not account for the observation that one easily notices a physical change in an unattended channel but cannot notice most semantic changes. An alternative possibility is that filtering actually results from habituation, as various data suggest (Hulstijn, 1979; Kraut, 1976; Kraut & Smothergill, 1978; Lorch et al., 1984; Lorch & Horn, 1986; Waters et al., 1977). Rather than the rejection of entire stimulus channels, there would be habituation to specific stimuli in these channels. Dishabituation to the channels presumably occurs whenever there is a change in the physical features of unattended stimulation or perhaps the occurrence of an item of special significance. For the relevant, attended channel, deliberate activation from the central executive would counteract habituation.

Derived Components of Processing

Many processing components that are not in the model (e.g., the working memory of Baddeley, 1986) are assumed to be formed from combinations of the memory stores and the central executive. It is not clear if the multifaceted nature of short-term memory performance (Crowder, 1982a) entirely reflects various derived components of processing or also subdivisions of the short-term store itself.

Model of Processing

It is possible to construct an information-processing model incorporating the eight premises above, with poststimulus time represented as a linear dimension of the model (Figure 1).

Alternative Views

Figure 1 has certain advantages that are not shared by alternative views in which there is only one type of memory storage (Craik & Lockhart, 1972; Wickelgren, 1973) or in which the stores are arranged in parallel (Shallice & Warrington, 1970) or with a flexible order (Broadbent, 1984). The model is compatible with Anderson's (1983) model, except that Anderson did not discuss the forms of sensory storage or the habituation mechanism of selective attention.

Research Issues

There are empirical predictions of the present approach related to sensory storage, short-term storage, the focus of attention, selective habituation, and working-memory processes.

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