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The Demonstration of Short-Term Consolidation

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In a dual-task paradigm, a visual display (T_1) containing characters (letters or symbols) was presented first, followed by an auditory signal (T_2) at various stimulus-onset asynchronies (SOAs). A speeded response to T_2 was required. When the information in T_1 had to be recalled later, response times to T_2 (RT_2) were elevated at short SOAs and decreased as SOA was increased. The effects on RT_2 were larger when there were more items to be remembered. We interpreted the results as evidence that encoding information into short-term memory (STM) involves a distinct process, which we call short-term consolidation (STC). The results suggested that STC has limited capacity and that it requires central processing mechanisms. Additional evidence suggested that no memory for T_1 was formed in STM when STC was not engaged.

OVERVIEW

The principal goal of this article is to demonstrate the involvement of central processing mechanisms in the encoding of information in short-term memory (STM). The article has the following structure: in the Introduction we include a selective review of work that has examined the issue of whether there are ''costs'' associated with ''encoding.'' This will motivate a discussion of what we might mean by encoding and we will distinguish between three different types of encoding: sensory encoding, perceptual encoding, and short-term consolidation (STC). Our main conclusion that STC is required for encoding information into short-term memory, and that STC re-

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quires central mechanisms. The Introduction is followed by a series of experiments in which we demonstrate and investigate short-term consolidation (STC). The demonstration of STC is based on a dual-task slowing effect observed in the performance of a simple concurrent task. The results suggest that STC requires central mechanisms that are also required to perform other central cognitive operations (such as response selection).

INTERFERENCE OF ENCODING ON CONCURRENT PROCESSING

The empirical work presented in this article made use of dual-task paradigms to investigate whether visual encoding would cause interference in concurrent tasks. The stimuli in the two tasks were presented in different modalities to minimize the likelihood of modality-specific interference (Pashler, 1989). In this section we briefly review previous work that investigated potential costs of encoding.

The general logic of these experiments was as follows. Suppose that encoding information presented visually requires central processing. In addition, suppose that a second task also requires central processing. To the extent that the processing requirements of the two tasks overlap in terms of the required central processing mechanisms, one would expect to find some interference between them. If the encoding task does not require central processing, then one would expect no interference between the two tasks, as long as the processing requirements of each task were distinct in all other ways.

Posner and Boies (1971) used this general logic to study the central cost of letter encoding. In the primary task, two letters were presented sequentially. The task was to decide whether the letters were the same or different (letter matching). On half of the trials, an auditory stimulus, called a probe, was also presented and subjects made a simple reaction to the probe. Posner and Boies (1971) argued that the probe task could be used to determine whether encoding the first letter in the matching task required a ‘‘capacity-limited attentional process.’’ They compared simple response times to probes presented just after the onset of the first letter, presumably when the subject was encoding this letter, with that for probes that occurred before the first letter. Simple response times for probes that occurred just after the presentation of the first letter were actually shorter than for probes that occurred before the letter (during the inter-trial interval). This suggested that there was no central involvement associated with encoding the first letter. Several other studies using a similar paradigm have produced similar results (Posner & Klein, 1973; Millar, 1975; Proctor & Proctor, 1979).

However, the conclusion that encoding visual information does not require central involvement has remained controversial. Several other investigators have performed experiments that were similar to those of the above researchers but in contrast to the null effects summarized above, they found significant dual-task costs associated with visual encoding. These experiments examined issues such as the relative probability of probe signals at various points during a trial (Ogden, Martin, & Paap, 1980), the duration of the first letter (Comstock, 1973), and temporal uncertainty in the onset of the second letter (Johnson, Forester, Calderwood, & Weisgerber, 1983).

Thompson (1987) also investigated the central demands of visual encoding, but in the context of a visual search task rather than letter matching. Subjects searched for targets defined by a single feature or a conjunction of features (Treisman & Gelade, 1980) in different blocks of trials, and a probe tone (requiring a simple reaction) was presented on half of the trials. Response times were longer in both the single feature condition and in the conjunction condition when the probe occurred immediately after the onset of the array. Thompson concluded that feature registration and feature integration are capacity-limited processes. Pashler (1994) criticized Thompson's (1987) experiment because the increase in simple response times could have been due to nonspecific effects, such as those described by Davis (1959), rather than to central involvement. Another criticism is that both encoding and search were required in Thompson's experiment, which makes it difficult to disentangle what produced the increase in simple response time.

There is still no consensus concerning the interpretation of the results from the Posner and Boies paradigm. On the one hand, some have concluded that encoding does have measurable costs implicating central involvement (Comstock, 1973; Johnson et al., 1983; Odgen et al., 1980). On the other hand, others have interpreted the same body of evidence as indicating essentially no costs of encoding and no central involvement (e.g., Pashler, 1994). One reason for this state of affairs is that the letter-matching paradigm makes it difficult to separate possible effects due to encoding from those associated with other aspects of the matching task. The Di Lollo and Moscovitch (1983; Dixon, 1986) paradigm, which also uses a matching task, raises similar difficulties. These other processes include such factors as anticipating the second stimulus, preparing for the matching process, performing the match, and preparing and engaging in the resulting response selection processes that are required to produce a response in the matching task. In the experiments that we describe we developed a paradigm in which such ambiguity is eliminated. Our primary task is simply to encode information for later report. This procedure eliminates the difficulties associated with the fact that matching operations were required in addition to encoding in the Posner and Boies (1971) paradigm, or both encoding and search in the Thompson (1987) experiment. Furthermore, the objection to Thompson's (1987) experiment raised by Pashler (1994) will not apply to our work (see Experiments 4, 5, and 7).

STAGES OF ENCODING

The work reviewed in the foregoing section suggests that it is necessary to distinguish between at least three kinds of encoding, and that it is likely that different types of limitations will be associated with each kind of encoding. We call these kinds of encoding sensory encoding, perceptual encoding, and short-term consolidation (STC).

Sensory Encoding

Sensory encoding has a number of important characteristics. First, it is massively parallel (Zeki, 1993) and it provides input to later systems through a collection of high-capacity channels that transmit information about different attributes of the stimuli (e.g., color, motion, stereopsis, and so on; Cavanagh, 1988; Treisman & Gelade, 1980; Zeki, 1993). Second, representations at this stage of encoding are susceptible to masking. Third, representations can give rise to sensory persistence (Coltheart, 1980). Fourth, sensory encoding (to a first approximation) is not subject to interference from concurrent cognitive processes, or from processes in other modalities.

Perceptual Encoding

Perceptual encoding is the process by which patterns are recognized. For objects that have representations in long-term memory, it is possible that perceptual encoding corresponds with the activation of a representation in long-term memory (Pashler & Carrier, 1996). In general, perceptual encoding can receive input from a variety of sensory channels (see Jolicœur & Cavanagh, 1992; Pinker, 1984). Representations at this stage of encoding contain information about the identity of patterns (e.g., letter identities; Duncan, 1980, 1983) and this information is no longer maskable. The representations remain active as long as they receive bottom-up support from sensory input. In the absence of bottom-up support, however, these representations decay rapidly unless subjected to further processing (Chun & Potter, 1995; Potter, 1976, 1993).

Short-Term Consolidation

We call the process of encoding information into short-term memory (STM) short-term consolidation (STC). The empirical work presented in subsequent sections in this article focuses on this kind of encoding. We provide evidence suggesting that STC takes time, that it takes more time to encode more information, and that STC requires central mechanisms that have been implicated in dual-task slowing, or the so-called PRP phenomenon (psychological refractory period; Bertelson, 1966; Pashler, 1994; Smith, 1967a; Telford, 1931).

There is good evidence for at least two different kinds of short-term memory (e.g., Baddeley, 1986; see Pashler & Carrier, 1996, for a recent review). We suspect that some form of STC is likely to be involved for each kind of short-term memory. However, this conjecture remains to be put to empirical test. In this article we focus on the form of short-term memory that is required to hold information about a visually-presented character and make a report a few seconds later that consists of typing the characters on a computer keyboard. Like Coltheart (1982, 1984), for expository purposes, we will call this kind of memory ‘‘durable storage.’’

In the absence of ongoing bottom-up support provided either by a physical stimulus or by sensory persistence, perceptual-encoding representations decay rapidly. If the output of perceptual encoding is subjected to STC, however, a representation in durable storage can be created, and some aspects of the information contained in the stimulus can be retained for further processing or delayed report. Representations in durable storage are not subject to the rapid decay that characterizes perceptual-encoding representations that do not have ongoing bottom-up support. The hypothesis that perceptual representations can be very short-lived and that consolidation of this information into a more durable form of memory is required for verbal report have been proposed by Potter (1976) and Chun and Potter (1995), who also provided supporting empirical evidence.

We recently developed a method that, we believe, allows us to demonstrate that STC—the process of encoding information into durable storage—requires central mechanisms that have been implicated in dual-task slowing paradigms (PRP). This result, per se, has implications for a wide range of paradigms and theories, ranging from the perception literature (e.g., Duncan, 1980), the PRP literature (e.g., Pashler, 1989, 1993, 1994), the AB literature (e.g., Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992), to the memory literature (e.g., Potter, 1993; Pashler & Carrier, 1996). We will return to the implications of this discovery in the General Discussion.

GENERAL METHOD

In this section we outline aspects of the methods that were common across the experiments and information on the subjects.

General Stimuli

Visual stimuli. The visual stimuli were black characters presented on a white background, on a SVGA color computer screen (cathode ray tube) controlled by a 486 or 586 CPU. In Experiments 1–5 and 7 the characters were presented for 250 ms and always followed by a pattern mask that was presented for 100 ms. In Experiment 6, a single letter was presented for 100 ms and followed by a 50 ms mask. The characters were presented at the center of the computer screen and subtended .85° (height) × .8° of visual angle. When more than one character was shown they were arrayed horizontally and the space between adjacent characters was .1°. The mask consisted of superimposed O and $ characters. The characters were uppercase letters or keyboard symbols. The letters or symbols were selected at random on each trial, without replacement, from the set of consonants excluding S and Z or from the following set of 9 characters: + ’’ ; & * (   ) $ −.

Auditory stimuli. The auditory stimuli were pure tones, presented for 100 ms, and with a frequency of 400 or 1200 Hz. They were presented by the speaker on the monitor and were well above threshold.

TABLE 1
Number of Subjects, Trials, and Outliers in Each Experiment

Experiment	Number of trials: Practice[a]	Number of trials: Experimental[a]	Subjects[b]	Mean age	Outliers
1	2 × 22 = 44	15 × 44 = 660	11 (6, 5)	24	2.4%
2	2 × 22 = 44	15 × 44 = 660	11 (5, 6)[c]	24	2.4%
3	2 × 22 = 44	15 × 44 = 660	11 (6, 5)	23	2.7%
4	2 × 24 = 48	12 × 48 = 576	30 (15, 15)	27	3.0%
4a	—	1 × 6 = 6	28	—	—
5	2 × 24 = 48	12 × 48 = 576	30 (15, 15)	26	4.2%
6	2 × 24 = 48	16 × 32 = 512	8 (4, 4)	26	2.4%
7	3 × 24 = 72	9 × 48 = 432	13 (5, 8)	24	1.9%

[a] Number of blocks × trials/block = trials total.
[b] Subjects total (females, males).
[c] One subject rejected for having 35% errors in Task_2 (original $N = 12$).

General Procedure

The visual display contained either 1 or 3 characters. Each trial began with a fixation box, at the center of the screen, that subtended 1.2° × 2.3° for 1-character displays, or 3.6° × 2.3° for 3-character displays. Subjects initiated each trial by pressing the spacebar of a computer keyboard. The fixation box then disappeared, and after a delay of 400 ms, a visual display (250 ms in Experiments 1–5 and 7; 100 ms in Experiment 6) containing either 1 or 3 characters was shown, followed by a mask (100 ms in Experiments 1–5 and 7; 50 ms in Experiment 6).

At varying SOAs following the visual display, a tone was presented and the subject was asked to make an immediate speeded response to the tone. The SOAs varied from experiment to experiment and are listed in the individual method sections. They often ranged from 350 to 1600 ms.

In some cases, the task associated with the visual display was to encode the characters so they could be recalled at the end of the trial. In these cases, at the end of the trial (following the response to a tone), the subject typed on a keyboard the remembered character(s). In other cases, the character(s) could be ignored. For these trials, the subject pressed the space bar at the end of the trial (following the response to the tone).

In all experiments except Experiment 5 (see below), subjects were instructed to respond immediately to the tone by pressing the ‘‘A’’ key if the tone had a high pitch or the ‘‘Z’’ key if the tone had a low pitch, with the middle and the index fingers of their left hand, respectively. Response times to the tone were measured from the onset of the tone to the button press. The auditory task was defined as the primary task in all experiments, and both speed and the accuracy were strongly emphasized. In Experiment 5, the same tones were used as in the other experiments, but the task was to press a single button regardless of which tone was presented. The task was thus a simple response time (simple RT) task rather than a two-alternative discrimination reaction time task.

Each subject performed about 40 practice trials followed by 500–600 experimental trials (exact numbers given in Table 1).

General Method of Analysis

Each trial produced a response to the tone and one or more responses to the visual display. Only trials in which the response to the tone was correct were included in the analyses. The trials were then screened for outliers using a slight modification of the procedure described by Van Selst and Jolicœur (1994). In this procedure, the data in each cell were sorted, and the most extreme observation was temporarily excluded from consideration. The mean and standard deviation of the remaining numbers was then computed. Cutoff values were established using the following equations:

$$V_{low} = \overline{X} - C * SD,$$
$$V_{high} = \overline{X} + C * SD.$$

The smallest and largest observation in the cell were then checked against the cutoff values, V_{low} and V_{high}. If one or both were outside the bounds, then they were defined as outliers and excluded from further consideration. If an outlier was found, then the algorithm was applied anew to the remaining data. The value of C depended on the sample size such that the estimated final mean was not influenced by sample size (see Van Selst & Jolicœur, 1994). This procedure resulted in an average loss of 2.1% of the correct trials in any particular analysis (see Table 1). When an error or an outlier was found in the auditory task, the entire trial was discarded, including the data for the memory task.

The results for the memory task were analyzed by computing the total number of characters recalled correctly without regard to order of report (when more than one character was in the visual display).

The results for both tasks were analyzed using the analysis of variance (ANOVA) in which all variables were within-subjects factors, except as noted in Experiments 4 and 5.

General Subjects

Most of the subjects were undergraduate students at the University of Waterloo who volunteered to participate for pay or for course credit. A few were graduate students or staff. All reported having normal or corrected-to-normal vision. All reported having normal hearing. Table 1 gives some statistics for each experiment.

Notation

In the experiments that follow there were two target stimuli, one visual and one auditory, and two responses. We will refer to the first target stimulus as T_1 and to the second as T_2. Each target stimulus, T_i, has associated with it a task, $Task_i$, a response, R_i, and sometimes a response time RT_i. The subscript always refers to the order in which the stimuli were presented. T_1 was a visual stimulus, and $Task_1$ required a delayed response, R_1. T_2 was an auditory stimulus that required an immediate response, R_2. Thus, R_2 actually occurred before R_1.

EXPERIMENT 1

Experiment 1 provided our first demonstration of short-term consolidation (STC). One or three letters were shown in the visual display (T_1). The task associated with the letters, $Task_1$, was simply to remember these letters and recall them at the end of the trial. The subject was asked to type either one or three letters on a computer keyboard at the end of each trial. T_2 was either a low-pitched or a high-pitched tone presented at one of 11 SOAs, ranging from 350 to 1350 ms, in 100 ms increments. $Task_2$ was a two-alternative discrimination reaction time task based on the pitch of the tone with a speeded response.

The parameters of the experiment were chosen so as to eliminate the possibility that early encoding (sensory or perceptual) would influence the results in Task_2. Our argument concerning this interpretation is based on prior results in the literature showing that simple characters can be encoded very rapidly (e.g., Sperling, Budiansky, Spivak, & Johnston, 1971; Sperling, 1960; Coltheart, 1982, 1984; Duncan, 1980, 1983; see also, Potter, 1976, 1993). Our goal was to provide sufficient time in the initial exposure of the visual display (T_1) such that the information could be safely assumed to have been completely encoded at the perceptual-encoding level. That is, that information about letter identities had been encoded by the time the tone (T_2) was presented. We argue that the initial 250 ms exposure duration and the additional 100 ms during which the mask was present provided ample time to encode three letters. And, certainly, this was enough time to perform perceptual encoding for one letter.

If response times to the auditory signal (T_2) are elevated at the shorter SOAs (350 ms), this will provide evidence for an interaction between a stage of processing required to perform the memory task (Task_1) and a stage of processing required to perform Task_2. Because the stimuli in the two tasks were in different modalities (visual in Task_1 and auditory in Task_2), the most likely locus of interaction between Task_1 and Task_2 is at a central stage of processing, where information from different sensory systems has converged, rather than within either modality (Pashler, 1989). Furthermore, because we believe that the information in T_1 was already encoded at least to the point of perceptual encoding (because of the long SOA), any interactions would implicate a process following perceptual encoding required to perform the memory task. We return to these points as we discuss the results in the following section.

Results and Discussion

The most interesting results are the response times to the tone (RT_2) for each SOA, depending on the number of letters to be remembered in Task_1. These results are shown in Fig. 1a. The results were clearcut and striking: There was a large effect of SOA, with a longer mean RT_2 at the 350 ms SOA that decreased gradually as the SOA was lengthened, $F(10, 100) = 27.64$, $MS_e = 787.83$, $p < .0001$. RT_2 was longer when T_1 contained 3 letters (451 ms) than when T_1 contained 1 letter (409 ms), $F(1, 10) = 31.91$, $MS_e = 3336.10$, $p < .0003$. Furthermore, the effects of the number of letters were larger for short SOAs than for longer ones, $F(10, 100) = 6.21$, $MS_e = 607.32$, $p < .0001$. The effect of the number of letters was 110 ms at an SOA of 350 ms and had a mean of 21 ms averaging over the three longest SOAs.

An additional analysis carried out on the results for the 1-letter condition showed that the effects of SOA were significant for this condition taken by itself, $F(10, 100) = 8.80$, $MS_e = 479.67$, $p < .0001$.

We also analyzed the accuracy of the Task_2 responses as a function of

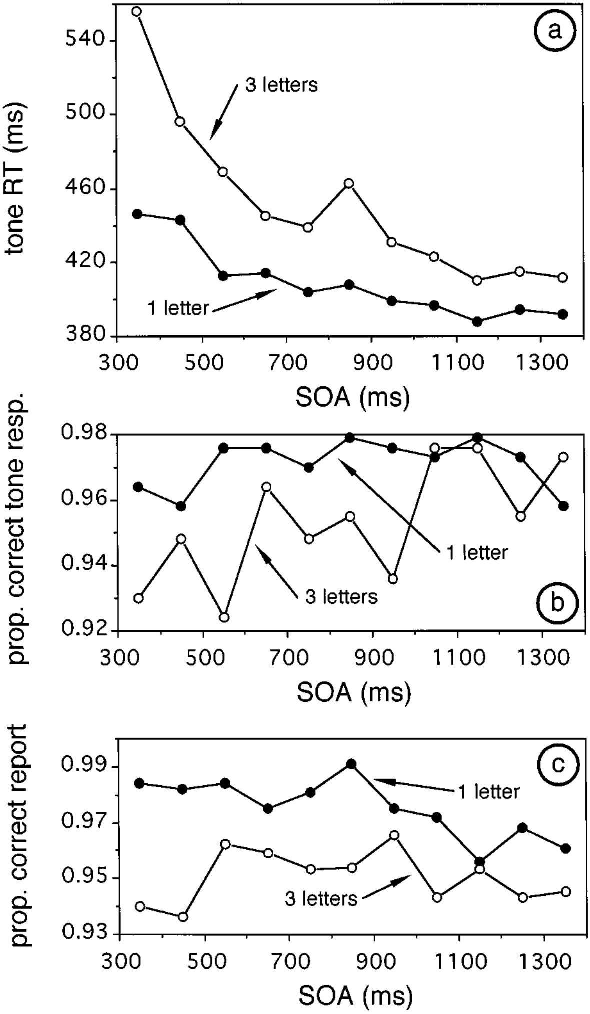

FIG. 1. Results from Experiment 1. (a) Mean response time (RT_2) to the tone (in milliseconds) for each SOA and each number of letters in the visual display. (b) Mean proportion of correct responses in the auditory task, for each SOA and each number of letters in the visual display. (c) Mean proportion of correct recall of the letters in the memory task, depending on the number of letters to be recalled and on the SOA at which the tone was presented.

$Task_1$ variables. The proportion of correct trials in the auditory task for each SOA and number of letters is shown in Fig. 1b. There was no main effect of SOA, $F(10, 100) = 1.36$, $MS_e = .001575$, $p > .21$. The difference between the 3-letter and the 1-letter conditions (1.8%) was not significant, $F(1, 10) = 3.14$, $MS_e = .005988$, $p > .11$, while the interaction between SOA and the number of letters approached significance, $F(10, 100) = 1.67$, $MS_e = .001229$, $p < .10$. The means suggest that accuracy in the auditory task decreased somewhat as SOA was shortened when 3 letters had to be remembered, whereas accuracy was more constant across the SOA manipulation in the 1-letter condition.

The recall proportion in the memory task for each SOA and number of letters is shown in Fig. 1c. Overall recall performance was very good, with an overall mean of .96. Recall was slightly better for the 1-letter condition (.975) than for the 3-letter condition (.950), $F(1, 10) = 4.89$, $MS_e = .007628$, $p < .052$. Neither the main effect of SOA, $F(10, 100) = 1.54$, $MS_e = .000784$, $p > .13$, nor the interaction between SOA and number of letters were significant, $F(10, 100) = 1.15$, $MS_e = .000902$, $p > .33$.

Merely trying to remember 1 or 3 letters was sufficient to produce a large cost in the auditory task. Because of the parameters used in the experiment, we believe that the costs observed in the auditory task were very unlikely to be associated with either sensory encoding or perceptual encoding. A sufficient amount of time (350 ms) was given to encode 3 letters up to the level of perceptual-encoding representations, and it surely must have been enough time to encode a single letter (e.g., Sperling et al., 1971). Nonetheless, large and systematic costs were observed in the auditory task even for single-letter trials.

The memory task ($Task_1$) we used in Experiment 1 is truly minimal. $Task_1$ was simply to remember 1 or 3 letters shown on a computer screen. Only after the response to the tone was there a response requirement associated with $Task_1$ (typing the letter(s) on a computer keyboard at the end of the trial). The response requirements of $Task_1$ were very unlikely to interfere with processing associated with the auditory task for two reasons. First, these responses were performed after the response to T_2. Second, $Task_1$ was unspeeded, which made it unlikely that R_1 occurred in close temporal proximity to R_2, which one would expect to be necessary in order to observe mutual interference (see Pashler, 1994; De Jong, 1993).

Several arguments allow us to rule out retention, *per se*, as the major cause of the interference on RT_2. The main argument against retention is that the response times in $Task_2$ decrease systematically as SOA was increased. This pattern of results is not consistent with a locus at retention because the retention requirements at long SOAs were the same as at short SOAs. One might argue that the retention requirements could have changed over time, with a greater load at short SOAs than at longer SOAs. This could have occurred if there was some memory loss taking place early in the trials, which would result in a lightening memory load as SOA increased. Two considerations allow us to rule out this interpretation. First, the results shown in Fig. 1c show that the probability of recall did not change significantly as SOA was increased, suggesting that the retention load did not decrease over time. Second, we performed separate analyses of trials in the 3-letter condition for which there had been perfect recall. On those trials, there was no loss of memory, but the results were essentially the same as those shown in Fig. 1a. This is not surprising because recall was very good and subjects recalled all the information correctly on a large majority of trials. These results are not consistent with an effect due to retention.

Although we argue that the effects of SOA were not likely caused by processes required to maintain information in durable storage, the asymptotic response times suggest strongly that maintaining information in durable storage does cause some dual-task interference. The asymptotic RT in the 3-letter condition was about 21 ms longer than that for the 1-letter condition. This result was expected based on several previous reports that holding a memory load causes some slowing of response times in concurrent speeded tasks and that a larger load is associated with more slowing (Logan, 1978; see also Shulman & Greenberg, 1971; Shulman, Greenberg, & Martin, 1971; Stanners, Meunier, & Headley, 1969).

Evidence for short-term consolidation is provided by the large effects of SOA and by the convergence of the functions for the 3-letter and 1-letter conditions, as SOA was increased. The choice of temporal parameters in the experiment allows us to argue that early encoding did not produce the dual-task slowing in RT$_2$. Furthermore, because the responses in Task$_1$ occurred after R$_2$ and because Task$_1$ was unspeeded, interference from response or output processes are also very unlikely. Given that retention has also been ruled out, we conclude that there is a process engaged by the memory task that occurs after the characters are identified (perceptual encoding), and that this process requires central limited-capacity mechanisms. We argue that this process, which we call short-term consolidation (STC), is the process of encoding information into durable storage. The strength of this argument will grow as we present additional evidence in the subsequent experiments and in the General Discussion, which will allow us to rule out other potential accounts of effects observed on RT$_2$ (Fig. 1a).

EXPERIMENT 2

Experiment 2 generalized the results of Experiment 1 to a different class of visual symbols. Rather than upper-case letters, the stimuli were the following nine symbols:

+ ″ ; & * ( ) $ −

We chose these symbols for two reasons. First, we wished to demonstrate that the effects obtained in Experiment 1 were not confined to highly overlearned materials like letters. Second, we hoped to demonstrate effects similar to those in Experiment 1 with materials that would be more difficult to recode phonologically. One interpretation of the results of Experiment 1 is that the costs observed in the auditory task were due to a capacity-demanding process of phonological recoding. Perhaps this type of coding is what STC actually involves for the form of durable storage (STM) required to remember a letter for later recall by typing. However, we hypothesize that STC is required for input to memory for material that we might call ‘‘purely visual.’’ As a first attempt to demonstrate this we chose materials that could be easily incorporated into the paradigm used in Experiment 1. The chosen symbols are less over-learned than upper-case consonants, and they should be more difficult to recode rapidly into phonological representations. Because the symbols are less over-learned than letters, we also expected the memory task to be more difficult in this experiment than in Experiment 1. The greater difficulty of the memory task should have at least two consequences. First, recall of the information at the end of the trial is likely to be inferior to what was found in Experiment 1. Second, the asymptotic cost of holding the information in durable storage on Task_2 should be larger than in Experiment 1.

Results and Discussion

The mean response times to the tone (RT_2) for each SOA, and for each number of symbols to be remembered in Task_1 are shown in Fig. 2a.

As in Experiment 1, there was a large effect of SOA, with a longer mean RT_2 at the 350 ms SOA that decreased gradually as the SOA was lengthened, $F(10, 100) = 11.17$, $MS_e = 2658.75$, $p < .0001$. RT_2 was longer when T_1 contained 3 symbols (574 ms) than when T_1 contained 1 symbol (503 ms), $F(1, 10) = 17.99$, $MS_e = 17011.13$, $p < .002$. However, unlike in Experiment 1, the effects of the number of symbols were relatively constant across SOA, $F < 1$.

The mean difference between the 3-symbol and 1-symbol conditions was computed across the longest five SOAs, to estimate the asymptotic difference across these two conditions. The mean difference was 71 ms, which was, as expected, larger than that found in Experiment 1 (21 ms over the longest three SOAs).

An additional analysis carried out on the results for the 1-letter condition showed that the effects of SOA were significant for this condition taken by itself, $F(10, 100) = 7.53$, $MS_e = 1806.31$, $p < .0001$.

As in Experiment 1, we analyzed the accuracy of the Task_2 responses as a function of Task_1 variables. The proportion of correct trials in the auditory task for each SOA and number of letters is shown in Fig. 2b. There was a marginal effect of SOA, $F(10, 100) = 1.85$, $MS_e = .001145$, $p < .065$, in which accuracy may have tended to be lower at the two shortest SOAs relative to the rest. Accuracy was slightly higher in the 1-symbol condition (.973) than in the 3-symbol condition (.955), and this effect was marginally significant, $F(1, 10) = 3.44$, $MS_e = .005639$, $p < .10$. The interaction between SOA and the number of letters was not significant, $F < 1$.

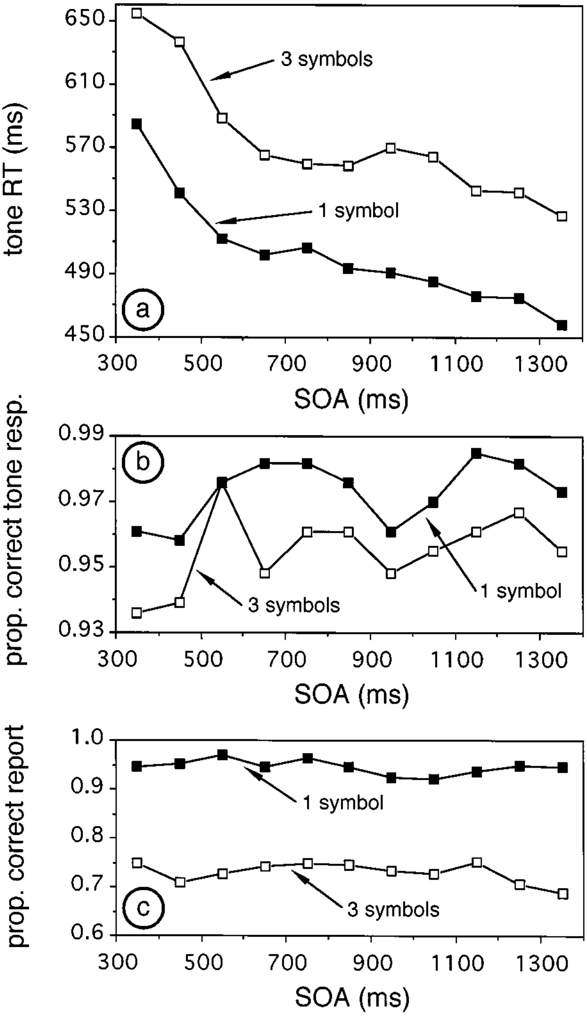

FIG. 2. Results from Experiment 2. (a) Mean response time (RT_2) to the tone (in milliseconds) for each SOA and each number of symbols in the visual display. (b) Mean proportion of correct responses in the auditory task, for each SOA and each number of symbols in the visual display. (c) Mean proportion of correct recall of the symbols in the memory task, depending on the number of symbols to be recalled and on the SOA at which the tone was presented.

The recall proportion in the memory task for each SOA and number of symbols is shown in Fig. 2c. Overall recall performance was good, with an overall mean of .837. Recall was better for the 1-symbol condition (.945) than for the 3-symbol condition (.730), $F(1, 10) = 206.65$, $MS_e = .453786$, $p < .0001$. The main effect of SOA was marginally significant, $F(10,$

100) = 1.87, $MS_e = .012052$, $p < .06$, but it is not clear how to interpret it. There may have been a slight tendency for recall to drop at the longest two SOAs. The interaction between SOA and number of symbols was significant, $F(10, 100) = 2.09$, $MS_e = .011404$, $p < .033$, perhaps indicating that the modest drop in recall at the longest SOAs was confined to the 3-symbol condition (Fig. 2c). These small effects were not observed in the other experiments in this article.

As in Experiment 1, response times to the tone were longer at shorter SOAs and gradually became shorter, and they were longer when 3 items had to be encoded than when there was only 1. We compared the results across experiments in analyses in which experiments was a between-subjects factor. The effects of SOA were so similar across experiments that there was no hint of an interaction, $F < 1$. However, there were three aspects of the results that were different. First, RT_2 was longer for symbols (538 ms) than for letters (430 ms), $F(1, 20) = 6.15$, $MS_e = 229960$, $p < .025$. Second, the interaction between SOA and number of items that was found for letters (Fig. 1a) was not found for symbols (Fig. 2a), and this produced a 3-way interaction in the combined ANOVA, $F(10, 200) = 2.04$, $MS_e = 1005.08$, $p < .035$. Third, recall performance was lower for symbols than for letters, and this difference was particularly marked for the 3-item conditions (3-letters, .950; 3-symbols, .730; 1-letter, .975; 1-symbol, .945), $F(1, 20) = 42.40$, $MS_e = .284641$, $p < .0001$ (Figs. 1c and 2c).

Some of the differences in results across Experiments 1 and 2 are likely simply due to the fact that letters are easier to process than symbols. In fact, we chose symbols because they should be less over-learned than letters. This appears to have had at least three effects. First, response times to the tone were generally longer, as expected if encoding the symbols into durable storage required a longer period of central involvement. Second, recall performance was worse for symbols than for letters, especially when there were 3 items to be remembered. And third, the asymptotic response time difference in $Task_2$ across the 3-symbol and 1-symbol conditions was larger than the corresponding difference in Experiment 1. We had hoped to find better evidence for convergence between the functions for the 3-symbol and 1-symbol conditions as SOA was lengthened. Clearly, this did not occur; number of symbols and SOA produced statistically additive effects. We address this issue in the General Discussion.

Although the change of material to be remembered undoubtedly affected the pattern of results, there were also some important similarities. First, the effects of SOA were similar and suggested again that encoding information into memory required central mechanisms, which was revealed by the slower response times in the auditory task. The short-term consolidation (STC) of symbols also produced easily measured dual-task interference in a simple concurrent cognitive task. Furthermore, as for letters, STC for symbols required more time when more information was to be remembered.

Because recall was lower, especially in the 3-symbol condition, there is a greater possibility than in Experiment 1 that the falling mean RT_2 as SOA was increased might reflect a change in memory load over time. As for Experiment 1, however, two aspects of the results allow us to rule out this possibility. First, as shown in Fig. 2c, there was no drop in recall as SOA was increased, which is not consistent with the notion that memory load was decreasing over time. Second, in a separate analysis, we compared RT_2 in the 3-symbol condition across trials in which all three were recalled vs trials in which only 2 symbols were recalled. The rate of change of RT_2 across SOA was not statistically different across the two conditions. This is not what should have happened, on the view that the change of RT_2 reflected a reduction in load from 3 to a lower load as SOA was increased. On this view, RT_2 should have been flat as a function of SOA, and uniformly high when all 3 symbols were recalled correctly. The decrease in RT_2 should have been observed only when less than 3 symbols were recalled correctly (in the ‘‘recall equals 2’’ condition in the present analysis). We also examined the mean RT_2 for trials on which only 1 symbol was recalled correctly when 3 had been shown (but we did not perform a statistical analysis for these results because some subjects produced empty cells). These means were similar to those for the other two cases ($recall = 2$ and $recall = 3$), providing evidence against the ‘‘changing load hypothesis.’’

Again, the results are consistent with the view that the reduction in RT_2 as SOA increased reflects a process of memory encoding, which we call STC. Although there were some differences across the results of Experiments 1 and 2, we believe that the similarities are more important than the differences from the point of view of evaluating whether the effects observed on RT_2, as a function of SOA, are due to a phonological recoding process that would require central involvement. The symbols that we chose are clearly quite difficult to recode into implicit phonology, yet the increase in mean RT_2 from Experiment 1 to Experiment 2 was only 108 ms. This difference is small relative to the change in the hypothesized difference in the difficulty of phonological recoding for letters vs symbols. Furthermore, the magnitude of this difference seemed to be the largest in the comparison between Experiments 1 and 2. In Experiment 3, the mean RT_2 was not as elevated as in Experiment 2, and in Experiment 4 the difference between the mean RT_2 for letters vs symbols was only 45 ms when the information had to be encoded. We return to the issue of phonological recoding in the General Discussion.

EXPERIMENT 3

The purpose of Experiment 3 was to extend the range of sampled SOAs used in Experiment 2 because it appeared to us as though the response times in the auditory task were still coming down even at the longest SOA used in that experiment. Experiments 3 was the same as Experiment 2 except that the increment along the SOA dimension was 150 ms for each additional SOA rather than 100 ms. This increased the range of SOAs from 350–1350 ms in Experiment 2 to 350–1850 ms in Experiment 3.

Results and Discussion

The mean response times to the tone (RT_2) for each SOA, and for each number of symbols to be remembered in $Task_1$ are shown in Fig. 3a. The results had the same general form as those of Experiment 2.

There was a large effect of SOA, with a longer mean RT_2 at the 350 ms SOA that decreased gradually as the SOA was lengthened, $F(10, 100) = 25.61$, $MS_e = 1311.79$, $p < .0001$. RT_2 was longer when T_1 contained 3 symbols (513 ms) than when T_1 contained 1 symbol (459 ms), $F(1, 10) = 19.04$, $MS_e = 9121.01$, $p < .0015$. As in Experiment 2, the effects of the number of symbols were relatively constant across SOA, $F < 1$.

An additional analysis carried out on the results for the 1-symbol condition showed that the effects of SOA were significant for this condition taken by itself, $F(10, 100) = 19.06$, $MS_e = 939.386$, $p < .0001$.

The asymptotic difference between the 3-symbol and 1-symbol conditions was 54 ms (estimated using the longest five SOAs). This difference was smaller than in Experiment 2 (71 ms) but still larger than in Experiment 1 (21 ms). These results converge with those of Experiment 2 in suggesting that holding 3 symbols in durable storage causes a larger increase in $Task_2$ response times than holding 3 letters.

As in Experiments 1–2, we analyzed the accuracy of the $Task_2$ responses as a function of $Task_1$ variables. The proportion of correct trials in the auditory task for each SOA and number of letters is shown in Fig. 3b. The effect of SOA was not significant, $F < 1$. Accuracy was slightly higher in the 1-symbol condition (.984) than in the 3-symbol condition (.978), and this effect was marginally significant, $F(1, 10) = 3.80$, $MS_e = .000483$, $p < .08$. The interaction between SOA and the number of letters was significant, $F(10, 100) = 1.94$, $MS_e = .000493$, $p < .05$. Given the similarity of the means (Fig. 3b), we do not ascribe much theoretical significance to these small effects.

The proportion of correct recall in the memory task for each SOA and number of symbols is shown in Fig. 3c. Overall recall performance was good, with an overall mean of .850. Recall was better for the 1-symbol condition (.971) than for the 3-symbol condition (.729), $F(1, 10) = 43.64$, $MS_e = .081463$, $p < .0001$. The main effect of SOA was significant, $F(10, 100) = 1.98$, $MS_e = .001702$, $p < .045$, but it is not clear how to interpret it (Fig. 3c). There may have been a slight tendency for recall to drop at the shortest and longest SOAs relative to the middle ones. The interaction between SOA and number of symbols was not significant, $F < 1$.

The results of Experiment 3 were very similar to those of Experiment 2. Most importantly, response times to the tone (RT_2) decreased as SOA was increased, and they were longer for the 3-symbol condition than for the

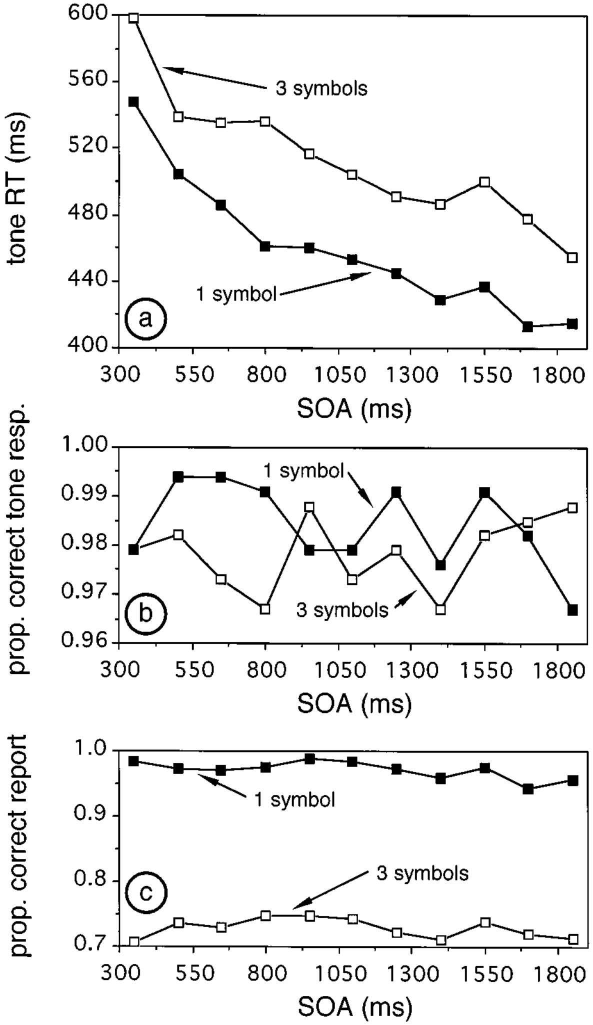

FIG. 3. Results from Experiment 3. (a) Mean response time (RT_2) to the tone (in milliseconds) for each SOA and each number of symbols in the visual display. (b) Mean proportion of correct responses in the auditory task, for each SOA and each number of symbols in the visual display. (c) Mean proportion of correct recall of the symbols in the memory task, depending on the number of symbols to be recalled and on the SOA at which the tone was presented.

1-symbol condition. The main motivation for Experiment 3 was to extend the range of SOAs used in Experiment 2. We were hoping to see the RT_2 functions reach a clear asymptote as the SOA was increased. Instead, as in Experiment 2, the functions continued to come down with a gentle slope as the SOA became longer and longer. We now suspect that this gentle decrease in RT_2 at the longer SOAs might be due to changing preparation as the SOA increases, with subjects becoming increasingly more prepared to process the tone (T_2) as time went by during the trial (De Jong & Sweet, 1994; Pashler, 1994). In this view, with very long SOAs, such as those in Experiment 3, the decrease in RT_2 with increasing SOA has two components. The first component reflects a decreasing probability that STC for T_1 is occupying central mechanisms at the time that T_2 is presented. The second reflects increasing preparation for $Task_2$. We will return to this issue in subsequent experiments and in the General Discussion.

As in Experiment 2, the effects of SOA and number of symbols were additive. This additivity contrasted with the interaction found in Experiment 1. We examined this effect further in Experiment 4.

EXPERIMENT 4

In Experiments 1–3 a probe tone (T_2) was presented after a visual display that contained information to be encoded into memory. Response times to the tone were systematically elevated at shorter SOAs and shortened as the SOA was increased. Furthermore, RT_2s were longer when three characters had to be remembered than when there was only one. We argued that these results reflected the operation of short-term consolidation (STC), a process required to encode the information into a durable form of memory, which we call durable storage.

The purpose of Experiment 4 was two-fold. First we wanted to determine whether the encoding costs observed as dual-task slowing in $Task_2$ were obligatory (and automatic in this sense) or optional. We expected, based on several considerations, that encoding information into durable storage would be an optional operation. Second Experiment 4 was designed to provide a control condition for possible general disruptive effects of the visual display on performance in the auditory task. For example, the elevated response times to the tone might reflect nothing more than a startle response or a disruption in the preparation for the auditory task. This type of argument might provide a basis for an account of the general pattern of RT_2s across the SOA manipulation. We do not believe that it can provide a convincing account of the effects of the number of symbols in the display, however. Nonetheless, Experiment 4 was designed to rule out the kind of general disruption account envisaged here.

In Experiment 4, the two types of visual material (letters vs symbols) that were used in Experiments 1–3 were intermixed at random from trial to trial.

Half of the subjects were instructed to remember letters (the ''encode'' condition) and to ignore symbols (the ''ignore'' condition); the other half were to remember symbols and to ignore letters. The experiment was otherwise the same as Experiments 1–3, except that we used a different set of SOAs (350, 500, 650, 800, 1200, and 1600 ms). At the end of trials for which the information was to be remembered, the subject was asked to type in the characters that had been presented at the beginning of the trial. On trials with material that could be ignored, the subject was instructed to press the space bar, which caused the program to proceed to the next trial.

If the response times (RT_2) in Experiments 1–3 were elevated because of a general disruptive effect of the visual display, or if STC is an obligatory process, then the same pattern of results should be found for all trials, regardless of whether the information was to be remembered or not. In contrast, if STC is an optional operation, and if that process caused the elevated response times in the earlier experiments, then RT_2 slowing should be only evident for trials in which the visual information had to be remembered. Furthermore, the slower response times for the 3-character condition than for the 1-character condition should only be found in the encode condition, where, according to our interpretation, a longer period of STC is required when more information is to be consolidated.

Although the effects of SOA should be smaller for the ignore condition than for the encode condition, we did not expect a completely null effect of SOA in the ignore condition. Instead, we expected a smaller effect, confined to the shortest SOAs that we sampled. The reason to expect some elevation in RT_2 even in the ignore condition is that some processing of the visual display was required to determine whether the information was to be encoded into durable storage or not. This internal choice was required because encode and ignore trials were intermixed at random throughout the test session. Thus, shortly after the onset of the visual display, the subject had to determine whether the characters had to be remembered, or whether they could be safely ignored. That is, they had to classify the symbols as either letters or symbols, and then submit the characters to STC if they belonged to the category of characters that had to be remembered. We expected the cognitive operations required to make this decision to require central mechanisms, which should result in some slowing of RT_2. This effect would be similar to the dual-task slowing observed on RT_2 for a $Task_1$ no-go trial, in a PRP experiment with a go/no-go $Task_1$ (e.g., Smith, 1967b; Bertelson & Tisseyre, 1969; De Jong, 1993).

In summary, if encoding information into durable storage does not require central involvement, then effects that we observed in Experiments 1–3 were caused by some other factor, such as a disruption of preparation for the auditory task. If so, we should observe the same pattern of results regardless of whether the information was to be encoded or not. In contrast, we hypothesized that encoding information into durable storage requires the involvement of a demanding central process, and that subjects would only engage this process when it was required by the task.

Results and Discussion

The mean response times to the tone (RT_2) for each SOA, for each number of symbols, and for the encode and ignore conditions in $Task_1$ are shown in Fig. 4a. The results from the encode condition, averaged across letters and symbols (top two functions) had the same general form as those in Experiments 1–3. The new results from this experiment are from the ignore condition, and they appear in the bottom two functions in Fig. 4a.

The results were analyzed using an ANOVA in which the material to be encoded (letters vs symbols) was a between-subjects factor, while SOA, encode/ignore, and the number of characters (1 vs 3) were within-subjects factors.

The most interesting effect in the ANOVA was the three-way interaction between encode/ignore, SOA, and the number of characters in the visual display, $F(5, 140) = 3.59$, $MS_e = 1321.05$, $p < .0045$, which is illustrated in Fig. 4a. When the characters had to be encoded, there was a larger effect of SOA for the 3-character condition than for the 1-character condition (as in Experiment 1). In contrast, when the information could be ignored (ignore condition), there were identical effects of SOA across the 1-character and 3-character conditions. The differential effects of SOA across different numbers of characters for the encode condition in contrast with the equivalent effects of SOA across different numbers of characters for the ignore condition is what created the three-way interaction.

As expected from the results in Fig. 4a, there was a larger effect of SOA for the encode condition than for the ignore condition, $F(5, 140) = 10.28$, $MS_e = 1358.15$, $p < .0001$. The difference between the 3-character condition relative to the 1-character condition was larger when the information had to be encoded than when it could be ignored, $F(1, 28) = 43.95$, $MS_e = 9674.59$, $p < .0001$.

The effects involving the material to be processed (letters vs symbols), in all cases but one, were clearly not significant, $F < 1$. The one exception—and the effect was statistically marginal—was the interaction between material (letters vs symbols) and whether the information had to be encoded or not, $F(1, 28) = 2.44$, $MS_e = 18869.61$, $p < .13$. The difference across letters vs symbols was small when the information could be ignored (ignore condition) (442 ms for letters; 455 ms for symbols). This difference was larger when the characters had to be encoded (486 ms for letters; 530 ms for symbols).

We also performed a separate ANOVA on the results from the encode condition, with type of material (letters vs symbols) as a between-subjects factor, and number of characters (1 vs 3) and SOA as within-subject factors. None of the effects involving material were statistically significant, $p > .27$

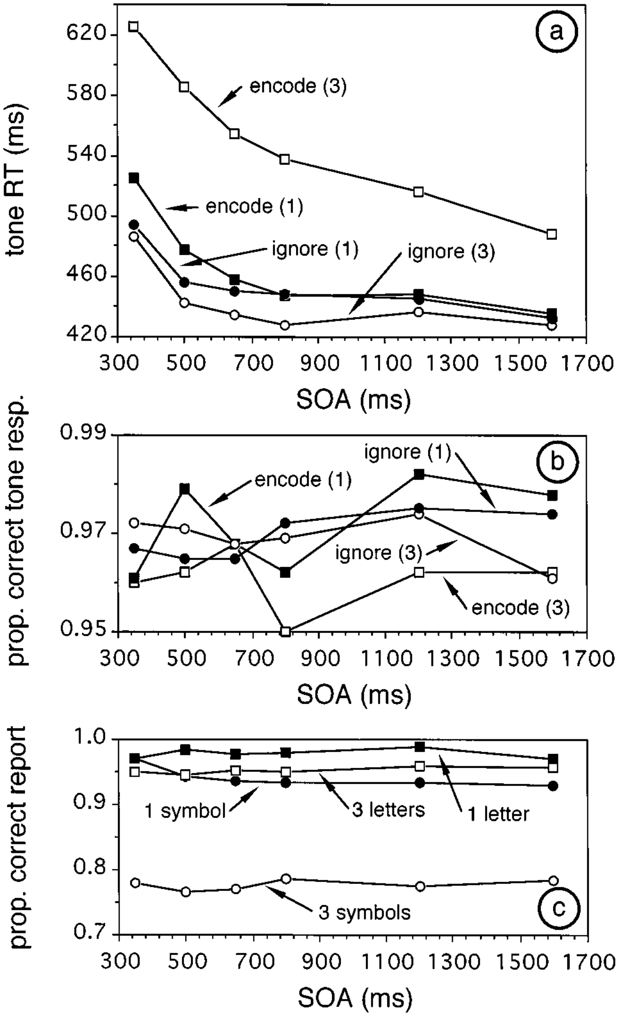

FIG. 4. Results from Experiment 4. (a) Mean response time (RT_2) to the tone (in milliseconds) for each SOA, each number of characters in the visual display, and for whether the visual information could be ignored or had to be encoded. (b) Mean proportion of correct responses in the auditory task, for each SOA, each number of characters in the visual display, and for ignore vs encode trials. (c) Mean proportion of correct recall of the characters in the memory task (encode condition), depending on the number of characters to be recalled, whether the characters were symbols or letters, and on the SOA at which the tone was presented.

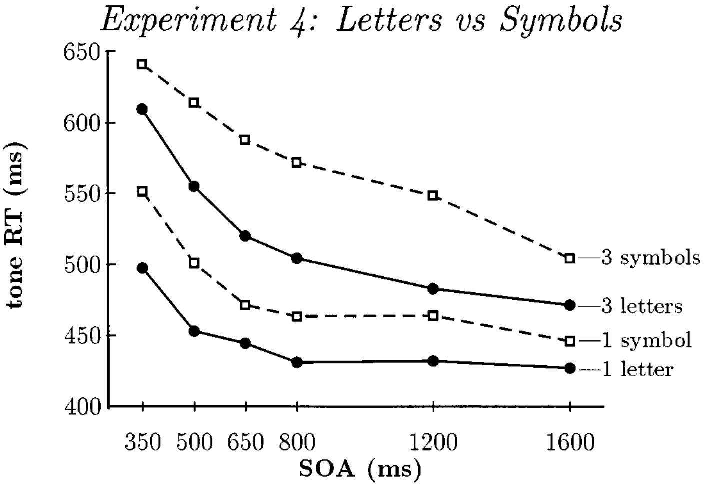

FIG. 5. Results from encode trials in Experiment 4 for letters vs symbols. Mean response time (RT_2) to the tone (in milliseconds) at each SOA and for each number of characters in the visual display.

in all cases. As expected from Fig. 4a, however, the interaction between number of characters and SOA was significant, $F(5, 140) = 3.31$, $MS_e = 2131.2415$, $p < .008$; reflecting the convergence in the two functions (3-character vs 1-character) as SOA was lengthened. The mean difference between the 3-character and 1-character conditions was 101 ms at the shortest SOA and only 51 ms at the longest SOA. Despite the non-significant 3-way interaction, we performed separate analyses of the results from the encode-symbols and encode-letters groups to see if the interaction between SOA and the number of characters was significant in both cases. The means are shown in Fig. 5. The interaction was significant for letters, $F(5, 70) = 6.22$, $MS_e = 873.043$, $p < .0001$, but not for symbols, $F(5, 70) = 1.10$, $MS_e = 3389.44$, $p > .37$.

The main effect of encode/ignore, $F(1, 28) = 33.72$, $MS_e = 18869.6$, $p < .0001$, of SOA, $F(5, 140) = 45.21$, $MS_e = 2411.82$, $p < .0001$, and of number of characters $F(1, 28) = 42.50$, $MS_e = 5845.6311$, $p < .0001$, were all highly significant. RT_2 decreased as SOA increased; RT_2 was longer for the encode condition than the ignore condition, and longer for the 3-character condition than for the 1-character condition.

An additional analysis carried out on the results for the 1-character condition to determine if the differential effects of SOA across the encode vs ignore conditions would be found when only 1 character had to be processed. The interaction between SOA and encode/ignore was significant, $F(5, 140) = 3.42$, $MS_e = 694.271$, $p < .006$, corroborating our interpretation that even when there was only 1 character, RT_2 was more elevated in the encode than the ignore condition at the shorter SOAs than at longer SOAs.

As in Experiments 1–3 we analyzed the accuracy of the $Task_2$ responses as a function of $Task_1$ variables. The proportion of correct trials in the auditory task for each SOA, number of characters, and for the encode/ignore conditions is shown in Fig. 4b. The effect of SOA was not significant, $F(5, 140) = 1.12$, $MS_e = .001286$, $p > .35$. However, the interaction between encode/ignore and number of characters was significant, $F(1, 28) = 5.76$, $MS_e = .000847$, $p < .025$. For the encode condition, accuracy was slightly lower when three characters were processed than when there was only one. This difference was not evident in the ignore condition. This effect is very small, however, given that the largest difference between the four means entering into the interaction was 1%. When this interaction was collapsed, a significant main effect of number of characters resulted, with slightly higher accuracy in the 1-character condition (.971) than in the 3-character condition (.965), $F(1, 28) = 4.68$, $MS_e = .001238$, $p < .04$. There were no other significant effects, $p > .056$ in all cases. As can be seen in Fig. 4b, accuracy was generally very high and any effects of $Task_1$ variables were small. We could not discern patterns of results that would lead us to doubt our interpretation of the response time results shown in Fig. 4a.

The recall proportion in the memory task for each SOA, number of characters, and letters vs symbols is shown in Fig. 4c. Overall recall performance was good, with an overall mean of .914. Recall was better for the 1-character condition (.967) than for the 3-character condition (.866), $F(1, 28) = 66.38$, $MS_e = .012910$, $p < .0001$. Recall was better for letters (.967) than for symbols (.862), $F(1, 28) = 27.68$, $MS_e = .036284$, $p < .0001$. There was also an interaction between material (letters vs symbols) and number of characters (1 vs 3), $F(1, 28) = 33.06$, $MS_e = .012910$, $p < .0001$. For letters, there was a smaller difference in recall level for the 1-character condition (.982) relative to the 3-character condition (.953). For symbols, there was a larger difference in recall level for the 1-character condition (.945) relative to the 3-character condition (.778). There were no other significant effects in the ANOVA, $p > .18$ in all cases. In particular, the effect of SOA was not significant, $F < 1$.

As in Experiment 1–3, the mean RT_2s in the encode condition of Experiment 4 were strongly affected by the number of characters to be remembered and they decreased as SOA increased. The results from the ignore condition provide additional support for our interpretation that the effects observed in the encode condition reflect a process of short-term consolidation (STC). For these trials, regardless of the number of characters, the mean RT_2 appeared to reach an asymptote at an SOA of about 500 ms. There was no evidence for a longer RT_2 in the 3-character condition than in the 1-character condition. In fact, a separate analysis of only the ignore trials showed that RT_2 was slightly longer in the 1-character condition (454 ms) than in the 3-character condition (443 ms), $F(1, 28) = 8.20$, $MS_e = 1440.40$, $p < .008$. This difference is easy to see in Fig. 4a (bottom two functions). Clearly, the additional time required to perform the auditory task in the encode-3-character condition relative to the encode-1-character condition could not be due to a general startle or disruptive effect of the visual display. If this had been so, the same pattern of results would have been observed in the ignore condition. Instead, a small reversed effect was found. We suspect that a slightly faster internal decision to ignore the visual information was possible when there were three characters as a result of a redundancy gain relative to the 1-character condition.

The results show that encoding information into durable storage is an optional operation under the cognitive control of the subject. In our view, early in each trial, the information in the visual display was encoded through the perceptual encoding stage. At that point, the activated representations were evaluated and an internal decision was made concerning the fate of the information. If the characters belonged to the class that had to be remembered, then the information was subjected to STC; otherwise it was not processed further. As we expected, there was a significant dual-task cost associated with the processing required to decide whether to subject the information to STC or to simply ignore it. This produced a significant effect of SOA on RT_2 even in the ignore condition, $F(5, 140) = 19.21$, $MS_e = 1393.77$, $p < .0001$, in a separate ANOVA of ignore trials. As can be seen in Fig. 4a, this effect was confined to the shortest SOA. In an additional analysis of the ignore condition in which we excluded the shortest SOA, the effects of SOA were no longer significant, $F(4, 112) = 2.06$, $MS_e = 1273.35$, $p > .09$. In our view, the SOA effect in the ignore condition reflects the decision to ignore the visual information. This decision must be based on a categorical analysis of the characters in the visual display. Furthermore, the control processes that decide whether to encode or to ignore the information require central mechanisms that have limited capacity. These processes may be the same as those required in no-go trials dual-task experiments in which the first task uses a go/no-go paradigm (e.g., Smith, 1967b). Another possibility is that, on a fraction of the trials, the subjects encode the information they were instructed to ignore, perhaps because of time pressure.

Unlike in the analysis of the combined results of Experiments 1 and 2, the effects of material (letters vs symbols) on RT_2 were not significant in this experiment. In particular, the interaction between SOA and number of characters for the encode condition did not interact with material in Experiment 4, whereas this effect was found in the comparison of Experiments 1 and 2. Nonetheless, the interaction was only significant for letters, in separate analyses performed on results from the encode-letters and the encode-symbols groups (see Fig. 5). This pattern of results suggests the possibility that the processing given to symbols in the encode condition was different from that given to letters. This issue is examined further in Experiment 5 and in the General Discussion.

One result was clearcut: RT_2 was longer at short SOAs in the encode condition relative to the ignore condition, and this was true even when only one character had to be remembered (Fig. 4a). We argue that this difference between the encode and ignore conditions reflects the process of short-term consolidation (STC), which is required in the encode condition but not in the ignore condition.

EXPERIMENT 4A

Experiment 4a was performed to provide a measure of how much information could be recalled in a trial in which the subject had, presumably, not subjected the visual information to STC. After the end of Experiment 4, the subjects were asked to perform six additional trials of the same sort as they had just performed. We told them that we wanted to measure their performance after they had become quite good at the task. Three characters were presented in each of these six trials. The 6th (and last) trial always involved the type of character that the subject had ignored throughout Experiment 4. However, at the end of this trial, the computer program displayed a message requesting that the information be recalled.

If information is encoded into durable storage ‘‘automatically,’’ then encoding would have taken place even on ignore trials. If so, recall in the last trial of Experiment 4a should be as good as in the encode-3 condition of Experiment 4. On the other hand, we believe that the response time results (RT_2) in Experiment 4 reflect the process of STC, or encoding into durable storage. On average, in the ignore condition, RT_2 was relatively unaffected by SOA and by the number of characters shown. Both of these results suggest that the information was not subjected to STC. If STC is necessary in order to establish a representation in durable storage, there should be no memory for the information shown in the visual display.

Results and Discussion

We only present the recall results from the last trial of Experiment 4a. The results are easy to summarize: recall performance was very poor. For subjects unexpectedly recalling letters, recall was at chance, while for those recalling symbols, performance was at chance for 10 of 16 subjects, but the overall performance of this group was significantly better than chance, although it was very much worse than for the encode condition in Experiment 4.

We examined the results separately for the subjects who were asked to recall letters on the 6th trial (who previously had to ignore letters) and those who were asked to recall symbols (who previously ignored symbols). The mean correct recall of letters was .58. The 95% confidence interval for this value was .14 to 1.02, which spans the performance level expected based on chance performance (.48). Thus, performance in this group was not significantly better than chance. Performance was also obviously much lower than in the encode condition of Experiment 4 (2.86 ± .22[1]). For the subjects who unexpectedly recalled symbols, the mean correct recall was 1.375, with the 95% confidence interval ranging from 1.11 to 1.64. The expected value of chance performance for this group was 1.0. Thus, the overall performance for the group was slightly better than expected by chance. We note, however, for 10 of the 16 subjects in this group, recall was exactly as expected by chance (recall of 1 symbol). Furthermore, recall was much lower than in the corresponding encode condition of Experiment 4 (2.34 ± .22[1]).

One might postulate that the first character in the display was the one recalled, because at least one character had to be encoded in order to decide whether the information had to be processed further or not. To examine this idea we computed mean recall for each character position in the display. In this case, recall was no better than chance for both groups and for each of the three character positions. For the group recalling letters, the expected value of chance recall was .16, and the 95% confidence interval was .11 to .39, for the first and second character positions, and −.11 to .27 for the third position. For the group recalling symbols, the expected value of chance recall was .33, and the 95% confidence interval was .16 to .71, for the first and second character positions, and .22 to .77 for the third position. Consistent with the above analyses, the notion that subjects encoded at least 1 character into memory (in order to determine whether to encode or not to encode) is not very likely because in that case the mean recall would have been equal to 1 plus an additional amount due to guessing. For the letter group, recall was less than 1, while for the symbols group it was only slightly higher than 1.

The results suggest that recall of information that was not subjected to STC is essentially null. This suggests that STC is necessary in order to create a durable representation in short-term memory. We consider the present results as suggestive rather than definitive because of the following caveat: one could argue that the poor recall performance was due to forgetting rather than encoding failure. Perhaps the unexpected request to recall the information that could, up to then, be ignored, caused some surprise or startle, which resulted in a loss of memory from durable storage. Although we cannot reject this argument, we do not find it convincing. Rather, we believe that the RT_2 results show that STC was not engaged when subjects knew that they did not have to encode the information in the visual display, and as expected their recall was at or only slightly above chance. Additional experimentation will be required to determine what can be remembered from objects that

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[1] The 95% within-subjects confidence interval (Loftus & Masson, 1994).

have been identified, but not subjected to STC. We hypothesize that explicit memory for such information will be very poor (Potter, 1976). In contrast, we expect that measures of implicit memory (Schacter, 1987) are likely to reveal the activation of perceptual-encoding representations for this information.

EXPERIMENT 5

As we reviewed in the Introduction, a number of researchers have used simple response time tasks as a way to estimate the effects of carrying out a concurrent task (e.g., Posner & Boies, 1971). Experiment 5 was in all ways identical to Experiment 4 except that simple RT was used in Task_2 instead of a two-alternative discrimination task. This experiment will allow us to relate our results to the large body of earlier work that employed simple RT in the probe task.

Results and Discussion

The mean simple response times (simple RT) to the tone (RT_2) for each SOA, for each number of characters, and for the encode and ignore conditions in Task_1 are shown in Fig. 6a. The results from the encode condition (open and filled squares) had the same general form as those in Experiments 1–4. The results from the ignore condition (open and filled circles) appear at the bottom of Fig. 6a.

The data were analyzed using an ANOVA as in Experiment 4 and a similar pattern of results was found. As in Experiment 4 there was a three-way interaction between encode/ignore, SOA, and the number of characters in the visual display, $F(5, 140) = 5.47$, $MS_e = 293.314$, $p < .0001$. When the characters had to be encoded, there was a larger effect of SOA for the 3-character condition than for the 1-character condition (as in Experiment 1). In contrast, when the information could be ignored (ignore condition), there were identical effects of SOA across the 1-character and 3-character conditions. The differential effects of SOA across different numbers of characters for the encode condition in contrast with the equivalent effects of SOA across different numbers of characters for the ignore condition resulted in the three-way interaction.

As expected from the results in Fig. 6a, there was a larger effect of SOA for the encode condition than for the ignore condition, $F(5, 140) = 5.36$, $MS_e = 697.110$, $p < .0002$. The difference between the 3-character condition relative to the 1-character condition was larger when the information had to be encoded than when it could be ignored, $F(5, 140) = 7.90$, $MS_e = 327.604$, $p < .0001$.

The effects involving the material to be processed (letters vs symbols) were not significant, $p > .13$ in all cases except one: As in Experiment 4, the one exception was the interaction between material (letters vs symbols)

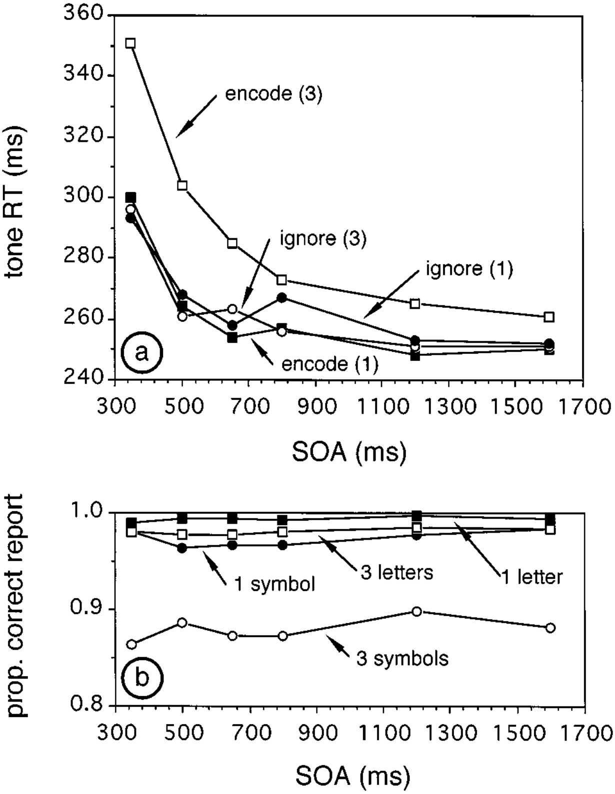

FIG. 6. Results from Experiment 5. (a) Mean simple response time (RT_2) to the tone (in milliseconds) for each SOA, each number of characters in the visual display, and for whether the visual information could be ignored or had to be encoded. (b) Mean proportion of correct recall of the characters in the memory task (encode condition), depending on the number of characters to be recalled, whether the characters were symbols or letters, and on the SOA at which the tone was presented.

and whether the information had to be encoded or not, $F(1, 28) = 5.31$, $MS_e = 4490.34$, $p < .03$. The difference across letters vs symbols was small when the information could be ignored (ignore condition) (265 ms for letters; 264 ms for symbols). This difference was larger when the characters had to be encoded (265 ms for letters; 287 ms for symbols).

The main effects of SOA, $F(5, 140) = 43.94$, $MS_e = 1207.52$, $p < .0001$, number characters, $F(1, 28) = 8.68$, $MS_e = 3403.25$, $p < .0065$, and of encode/ignore, $F(1, 28) = 5.68$, $MS_e = 4490.34$, $p < .025$, were all significant. RT_2 decreased as SOA increased; RT_2 was longer for the encode condition than for the ignore condition, and longer for the 3-character condition than for the 1-character condition.

A separate analysis of the results from the encode condition produced

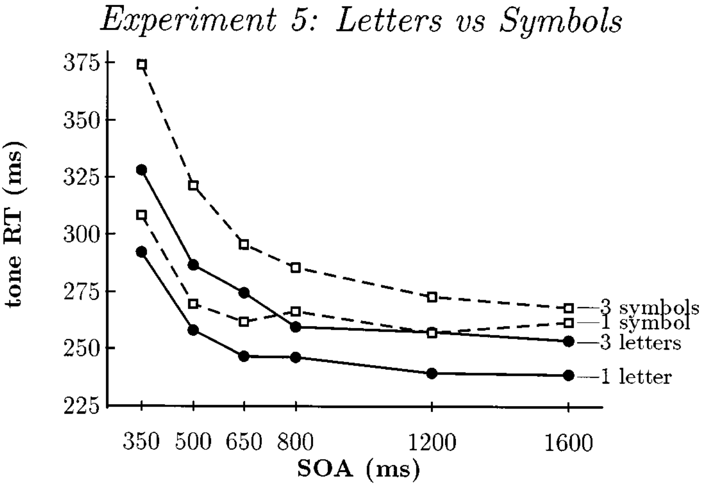

FIG. 7. Results from encode trials in Experiment 5 for letters vs symbols. Mean response time (RT_2) to the tone (in milliseconds) at each SOA and for each number of characters in the visual display.

a significant interaction between the number of characters and SOA, $F(5, 140) = 8.34$, $MS_e = 442.026$, $p < .0001$, reflecting the convergence of the RT_2 functions as SOA was lengthened. The interaction between materials (letters vs symbols), SOA, and number of characters was not significant, $F(5, 140) = 1.83$, $MS_e = 442.026$, $p > .11$. The difference between the 3-character condition and the 1-character condition was 51 ms at the shortest SOA but only 11 ms at the longest SOA. Separate analyses were also performed for each type of character. The interaction between SOA and number of characters was significant in both cases: $F(5, 70) = 3.65$, $MS_e = 166.652$, $p < .006$, for letters, and $F(5, 70) = 5.42$, $MS_e = 717.399$, $p < .0003$, for symbols. The means can be seen in Fig. 7.

An additional analysis carried out on the results for the 1-character condition to determine if the differential effects of SOA across the encode vs ignore conditions would be found when only 1 character had to be processed. The interaction between SOA and encode/ignore was not significant, $F < 1$. Thus, unlike the results of Experiment 4, in which there was a clearcut cost of encoding 1-character, over and above the cost associated with the decision to encode vs not to encode, there was no evidence for this additional cost in Experiment 5. Perhaps this effect would have been observed if we had presented tones at shorter SOAs than 350 ms. Here is one line of argument that would suggest this possibility. There was some suggestion that the memory task, itself, may have been easier to perform when paired with a simple RT (see next paragraph) task than when paired with a choice task (compare recall for 3 symbols in Experiments 4 and 5; Figs. 4c and 6b). If so, it is possible that the time to perform STC for 1 letter may have been shorter in Experiment 5 than in Experiment 4. Thus, STC may have already been completed in Experiment 5, 350 ms after the onset of 1 character to be encoded. If so, testing at shorter SOAs might have revealed the process of STC for 1 character even when using simple RT in $Task_2$. The fact that RT_2 was still obviously elevated in the ignore conditions at 350 ms SOA, however, poses some difficulties for the above argument. What we can say unambiguously is that using equivalent SOAs, the two-alternative discrimination procedure (e.g., Experiment 4) revealed the encoding costs for 1 character over and above those associated with the decision to encode or ignore, while the simple RT procedure did not. This difference could explain why there has been some controversy concerning the issue of whether there are costs of encoding 1 character when the probe task used a simple RT procedure.

The recall proportion in the memory task for each SOA and number of symbols is shown in Fig. 6b. Overall recall performance was good, with an overall mean of .958. Recall was better for the 1-character condition (.984) than for the 3-character condition (.931), $F(1, 28) = 28.89$, $MS_e = .008842$, $p < .0001$. Recall was better for letters (.988) than for symbols (.927), $F(1, 28) = 10.89$, $MS_e = .030004$, $p < .003$. There was also an interaction between material (letters vs symbols) and number of characters (1 vs 3), $F(1, 28) = 16.64$, $MS_e = .008842$, $p < .0003$. For letters, there was a smaller difference in recall level for the 1-character condition (.994) relative to the 3-character condition (.981). For symbols, there was a larger difference in recall level for the 1-character condition (.974) relative to the 3-character condition (.881).

In addition, the 3-way interaction between SOA, number of characters, and letters vs symbols, which can be seen in Fig. 6b, was significant, $F(5, 140) = 2.60$, $MS_e = .000452$, $p < .03$. This interaction might reflect the slight divergence in recall across the 1 vs 3 variable for symbols, at the shortest SOA, in contrast with the relatively constant difference between 1 and 3 for letters. There were no other significant effects in the ANOVA, $p > .08$ in all cases.

Because recall appeared to be superior in Experiment 5 compared with that in Experiment 4, we also performed an ANOVA in which we compared the recall results across experiments. Recall was indeed significantly better in Experiment 5 than in Experiment 4, $F(1, 56) = 11.27$, $MS_e = 0.193522$, $p < .0015$. It seems likely that subjects found the simple RT task (Experiment 5) easier to perform than the two-alternative discrimination task (Experiment 4), and this difference may have allowed the subjects in Experiment 5 to prepare better for the memory task (even though responses were obviously quite fast, as can be seen in Fig. 6a). This type of trade-off between tasks is consistent with our claim that some aspect of the memory task requires central involvement. If encoding information into durable storage was somehow capacity-free and did not require central processing, then it is not clear why we should have observed this trade-off across Experiments 4 and 5.

The main purpose of Experiment 5 was to investigate whether using simple RT in $Task_2$ would produce a qualitative pattern of results that would mirror what was found with a two-alternative discrimination task. As expected, overall response times were faster with the simple RT than with the two-alternative discrimination task (compare Figs. 4a and 6a). However, the patterns of results were similar in many ways. The effects of SOA for the encode condition were similar in general form across procedures. Also, in the simple RT task, there was a clear-cut difference between the encode-1 and encode-3 conditions, revealing a sensitivity to the amount of information to be remembered. The results of Experiment 5 thus provide converging evidence for the operation of STC in the encode condition even when simple RT is used as the probe task. There were two differences across Experiments 4–5. The first was that the two-alternative discrimination task was more sensitive than the simple RT task to the operation of STC when only 1 character had to be remembered. The other difference was that we found convergence between the encode-3 and encode-1 conditions as SOA was lengthened, for both letters and symbols in Experiment 5, but only for letters in Experiment 4.

EXPERIMENT 6

Experiment 6 was carried out for two principal reasons. First, as we mentioned in Experiment 3, we became concerned that when very long SOAs were used in the experiment, the decrease in RT_2 with increasing SOA might include a component of task preparation, rather than uniquely reflecting the operations of STC. We attempted to lower the likelihood that there would be large changes in task preparation by sampling a smaller range of SOAs. The elimination of very long SOAs should give us a measure of STC that is less likely to be contaminated by effects of changing preparation.

In Experiments 1–5, the shortest SOA was 350 ms. This choice for the shortest SOA was deliberate. We wanted to ensure that all phases of early encoding would be completed before we began probing the system for evidence of concurrent cognitive activity. Given that we now have good evidence for STC under the conditions of Experiments 1–5, we wished to examine the shape of the RT_2 function of SOA for shorter SOAs than 350 ms. This was the second purpose of Experiment 6. Given that several studies suggest that that time required to perform sensory and perceptual encoding is very brief (e.g., Sperling et al., 1971; Sperling, 1960; Coltheart, 1982, 1984; Duncan, 1980, 1983) we expected that STC would begin very soon after the onset of the visual display, especially when only one character is presented. Thus, we expected to discover that RT_2 would continue to increase as SOA was shortened to values less than 350 ms.

In Experiment 6, Task_1 was the delayed recall of a single letter, chosen from the same set as that used in Experiment 1. As in Experiments 1–3, the subject was to encode the character on every trial. Because a single letter was to be encoded, we shortened the exposure duration of T_1 to 100 ms (from 250 ms in Experiments 1–5). The mask duration was 50 ms (reduced from the 100 ms duration used in Experiments 1–5).

Task_2 was identical to that used in Experiments 1–4 (a two-alternative discrimination task). The SOA between the visual display and the tone was either 0, 50, 150, 250, 350, 450, 550, or 650 ms, chosen at random from trial to trial, with equal probability. We expected that this choice of SOAs would make it unlikely that subjects would change their relative preparation for the two tasks, even at the longest SOA.

Results and Discussion

Figure 8a shows the mean choice response times to the tone (RT_2) for each SOA. The results were clearcut and striking: the mean RT_2 was highest at 0 ms SOA, RT_2 decreased linearly as SOA increased until it reached an obvious asymptotic value at an SOA of 350 ms. This pattern of results was reflected by a significant effect of SOA in an ANOVA in which SOA was the only (within-subjects) factor, $F(7, 49) = 11.58$, $MS_e = 633.025$, $p < .0001$. There was no hint of any difference in mean RT_2 across the last 4 SOAs ($F < 1$, in a separate ANOVA that considered just these 4 SOAs).

We also analyzed the accuracy of the Task_2 responses as a function of the SOA between T_1 and T_2. The means are shown in Fig. 8b. Accuracy was very good, with a mean proportion of .977 correct trials, and accuracy did not vary with SOA, $F(7, 49) = 1.18$, $MS_e = .000374$, $p > .32$.

The mean recall for the letter was .988, and recall did not vary across SOA, $F(7, 49) = 1.40$, $MS_e = .000169$, $p > .22$, as can be seen in Fig. 8c.

The pattern of results was consistent with the view that central involvement, in the present paradigm, begins very shortly after the presentation of the visual display and is almost always finished by 350 ms. The shorter SOA at which the function reached asymptote than in Experiments 1–3 (and 7) was not expected. Several explanations are possible. Perhaps presenting a single letter on every trial reduced the total processing requirements of the encoding task compared to when different numbers of letters could be presented on different trials, and the reduced load may have allowed tone processing to begin earlier. Perhaps intermixing trials with different numbers of characters added variability to the encoding processes, which was reflected in the results as a longer inflection SOA (Experiments 1–3, and 7). It is also possible that the inclusion of trials in which three characters had to be encoded may have caused a greater buildup of proactive interference during the course of the experiment, which would be observed as a longer and more variable duration of STC.

We were particularly impressed with the sharpness of the transition be-

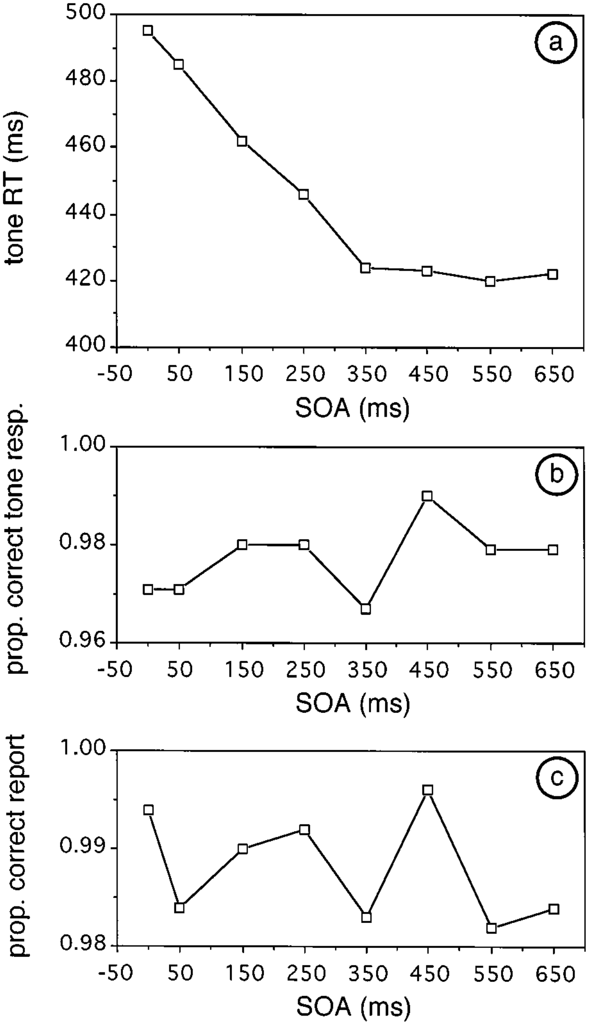

FIG. 8. Results from Experiment 6. (a) Mean response time (RT_2) to the tone (in milliseconds) for each SOA. (b) Mean proportion of correct responses in the auditory task for each SOA. (c) Mean proportion of correct recall of the letter in the memory task, depending on the SOA at which the tone was presented.

tween the sloped portion of the RT_2 function and the asymptotic portion. We believe that we found this result because we used a more limited range of SOAs, which probably prevented a change in the preparation state for the auditory task during the trials (De Jong & Sweet, 1994). The results were as expected if encoding even a single letter in durable storage requires central mechanisms.

Because we used very short SOAs in this experiment, we cannot rule out the possibility that some of the dual-task slowing observed in $Task_2$ could be associated with processes of encoding taking place prior to STC. In fact, it is likely that such processing was reflected in the response time in $Task_2$ because processing time taking place before STC would delay the onset of STC, and therefore the time at which STC would terminate, thereby altering the period of time during which processing in $Task_1$ can interfere with processing in $Task_2$. These considerations are clarified by the general model of task interactions and the computer simulations of the results that we present in the General Discussion.

EXPERIMENT 7

In Experiments 4 and 5, a larger effect of SOA was observed, especially at shorter SOAs, when information had to be encoded than when it could be ignored. We attributed the increase in RT_2 between the encode and ignore conditions to the process of STC, which was required only in the encode condition. The increase in RT_2 in the ignore condition at the shortest SOA relative to the longer SOAs was attributed to the decision processes required to determine whether to encode or ignore the visual information. If this interpretation of the SOA effect in the ignore condition is correct, we should be able to eliminate it (or at least significantly reduce it) by removing the on-line decision requirement of the task. This was the main purpose of Experiment 7. One or three letters were shown at the beginning of each trial. In some blocks of trials, the information had to be recalled at the end of the trial (as in Experiments 1–3). In other blocks, however, the letters could be ignored. The ignore blocks provide a similar type of control condition as the ignore trials in Experiments 4–5, but removes the on-line decision component of the task.

If the elevated RT_2 at short SOAs in the ignore trials of Experiments 4–5 were caused by the need to decide whether to encode or ignore, then this effect should not be found in Experiment 7.

The temporal parameters (duration of the visual display, of the mask, and the SOAs) in Experiment 7 were the same as in Experiment 4. The visual stimuli were always letters (1 or 3). Ignore vs encode trials were blocked rather than intermixed (as in Experiments 4–5). There were two encode blocks for every ignore block.

Results and Discussion

Figure 9a shows the mean response times to the tone (RT_2) for each SOA, each number of letters, and for the encode and ignore conditions. The results from the encode condition (top two functions) had the same general form as those in Experiments 1 and 4. The results from the ignore condition, at the bottom of the Fig. 9a were now only minimally affected by SOA.

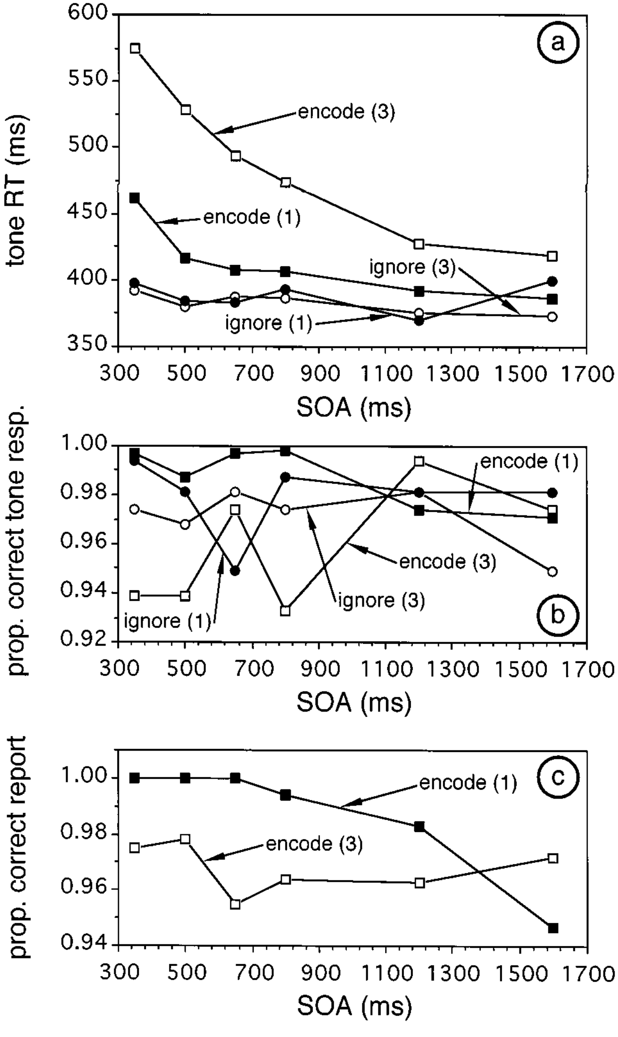

FIG. 9. Results from Experiment 7. (a) Mean response time (RT_2) to the tone (in milliseconds) for each SOA, each number of characters in the visual display, and for whether the visual information could be ignored or had to be encoded. (b) Mean proportion of correct responses in the auditory task, for each SOA, each number of characters in the visual display, and for ignore vs encode trials. (c) Mean proportion of correct recall of the characters in the memory task (encode condition), depending on the number of characters to be recalled and on the SOA at which the tone was presented.

The results were analyzed using an ANOVA in which SOA, encode/ignore, and the number of characters (1 vs 3) were within-subjects factors. The interaction between encode/ignore, SOA, and the number of characters in the visual display was highly-significant, $F(5, 60) = 6.47$, $MS_e = 574.803$, $p < .0001$. When the characters had to be encoded, there was a larger effect of SOA for the 3-character condition than for the 1-character condition (as in Experiments 1, 4, and 5). In contrast, when the information could be ignored (ignore condition), there were identical effects of SOA across the 1-character and 3-character conditions. The differential effects of SOA across different numbers of characters for the encode condition in contrast with the equivalent effects of SOA across different numbers of characters for the ignore condition is what created the three-way interaction.

A separate ANOVA performed on the results from encode blocks revealed a significant interaction between SOA and number of letters, reflecting the significant convergence between the two functions as SOA was lengthened, $F(5, 60) = 14.84$, $MS_e = 562.751$, $p < .0001$. The difference between the 3-letter and 1-letter condition was 113 ms at the shortest SOA but only 32 ms at the longest SOA.

As expected from the results in Fig. 9a, there was a larger effect of SOA for the encode condition than for the ignore condition, $F(5, 60) = 16.95$, $MS_e = 1150.61$, $\mathrm{p} < .0001$. The difference between the 3-character condition relative to the 1-character condition was larger when the information had to be encoded than when it could be ignored, $F(1, 12) = 36.80$, $MS_e = 3398.98$, $p < 0.0001$.

The main effects of SOA, $F(5, 60) = 23.91$, $MS_e = 1239.25$, $p < .0001$, encode/ignore, $F(1, 12) = 32.76$, $MS_e = 9644.68$, $p < .0001$, and number of characters, $F(1, 12) = 49.41$, $MS_e = 1840.75$, $p < .0000$, were all highly significant. RT_2 decreased as SOA increased; RT_2 was longer for the encode condition than the ignore condition, and longer for the 3-character condition than for the 1-character condition.

An additional analysis carried out on the results for the 1-character condition to determine if the differential effects of SOA across the encode vs ignore conditions would be found when only 1 character had to be processed. The interaction between SOA and encode/ignore was significant, $F(5, 60) = 6.46$, $MS_e = 648.565$, $p < .0001$, corroborating our interpretation that even when there was only 1 character, RT_2 was more elevated in the encode than the ignore condition at the shorter SOAs than at longer SOAs.

We also performed a separate ANOVA on the results from the ignore trial blocks. SOA and number of letters were both within-subjects factors. Only the effects of SOA were statistically significant $F(5, 60) = 2.45$, $MS_e = 581.077$, $p < .045$; $p > .14$ for number of letters and for the interaction between SOA and number of letters. The effects of SOA seemed truly minimal across the first four SOAs, however, which was corroborated in a separate ANOVA on just these SOAs, $F(3, 36) = .20$, $MS_e = 1207.63$, $p > .89$.

The significant effects in the ANOVA including all six SOAs appears to be due to the shorter RT_2 at the longer SOAs, which were now expected if some differential task preparation resulted in a gradual decline in RT_2 as SOA became very long.

As in previous experiments, we analyzed the accuracy of the $Task_2$ responses as a function of $Task_1$ variables. The proportion of correct trials in the auditory task for each SOA, number of characters, and for the encode/ignore conditions is shown in Fig. 9b. The three-way interaction between SOA, number of letters, and encode vs ignore was significant, $F(5, 60) = 3.29$, $MS_e = .001276$, $p < .011$. It appears that slightly lower accuracy in $Task_2$ occurred in the encode blocks than in the ignore blocks, at shorter SOAs only, and that this difference was larger when 3 letters were encoded than when only 1 letter was encoded. These results are generally consistent with the response time results and suggest that encoding the information in the visual display made it more difficult to perform the speeded tone task. Various other effects in the ANOVA were also significant, as expected from collapsing the three-way interaction displayed in Fig. 9b. There were more errors when there were more letters, $F(1, 12) = 13.48$, $MS_e = .001536$, $p < .0035$. The effects of SOA were larger when there were 3 letters than when there was only 1, $F(5, 60) = 3.25$, $MS_e = .001576$, $p < .015$. There was also a marginal interaction between SOA and block (ignore vs encode), $F(5, 60) = 2.30$, $MS_e = .001668$, $p < .06$. There were no other significant effects, $p > .28$ in all cases.

The recall proportion in the memory task for each SOA and number of letters is shown in Fig. 9c. Overall recall performance was good, with an overall mean of .978. Recall was better for the 1-character condition (.987) than for the 3-character condition (.968), $F(1, 12) = 22.88$, $MS_e = .000645$, $p < .0004$. Recall declined slightly as SOA was lengthened, $F(5, 60) = 3.34$, $MS_e = .000889$, $p < .01$, but this effect was confined to 1-letter trials, which produced an interaction between number of letters and SOA, $F(5, 60) = 7.48$, $MS_e = .000470$, $p < .0001$.

The results of Experiment 7 provide strong converging evidence supporting our interpretation of the results of Experiments 1–6. As in the previous experiments, there were large effects of SOA in the encode condition, which were modulated by the amount of information to be encoded. In contrast, the effects of SOA were minimal in the ignore condition. These findings are as expected if the obvious effects of SOA in the ignore conditions of Experiments 4–5 were caused by decision processes associated with the online decision to encode or ignore the visual information. Removing this decision component of the task by blocking the trials eliminated the effects of SOA at short SOAs, as we expected.

The results provide additional support for the notion that encoding information into durable storage is an optional operation under the subject's control. The results also provide strong evidence against nonspecific (e.g., startle) effects associated with the presentation of a visual stimulus just before the tone in the speeded auditory discrimination task.

GENERAL DISCUSSION

Short-Term Consolidation (STC)

We interpret the results of these experiments as a demonstration of the process of short-term consolidation (STC). In our view, STC is a process that mediates the transfer of information generated from sensory input to storage in durable storage (probably STM). We believe that when this process is engaged, the performance of a concurrent task is slowed: STC causes dual-task slowing. This dual-task slowing is itself one of the most important properties of STC. It was observed in dual-task paradigms in which two stimuli were presented in different sensory modalities, reducing the likelihood that the interference we observed resulted from within-modality capacity limitations (Pashler, 1989).

In Experiments 1–4 and 6–7, the concurrent task was a speeded discrimination based on the pitch of a tone. Evidently, STC caused one or more stages of processing required to perform the auditory task either to wait, to slow down, or perhaps both. Which of these alternatives is correct cannot be determined on the basis of the present results, and investigating this issue is an important problem for future work. The possibility that a stage of processing mediating performance in the tone task may have had to wait would make the present phenomenon similar to the one observed when both tasks require a speeded response (Pashler, 1994; Johnston, McCann, & Remington, 1995; De Jong, 1993). Based on recent work on dual-task slowing, a likely stage of processing required for the auditory task that would be subject to postponement is response selection (McCann & Johnston, 1992; Pashler, 1994; Van Selst & Jolicœur, 1997). If the interference we observed was due to postponement, then it would be likely that STC processes required for the memory task postponed response selection in the auditory task. It is also possible, however, that capacity sharing between the encoding task (STC) and one or more stages of processing in the tone task may have produced the results.

In Experiment 5 we used a simple reaction time task as the speeded auditory Task$_2$. For a simple RT task it seems awkward to call the stage of processing that was subject to dual-task interference ‘‘response selection,’’ because there was only one response. Although the task bears the name of ‘‘simple reaction time,’’ the psychology associated with it is anything but simple (see Welford, 1980). In any case, several studies in the PRP (psychological refractory period) literature have shown that some aspect of the simple RT task is subject to dual-task slowing when the simple RT task is the second of two speeded tasks (e.g., Karlin & Kestenbaum, 1968; Schubert, 1996; Van Selst & Jolicœur, 1997). We hypothesize that central processing is required to determine whether sufficient evidence has accumulated to release the (already selected) response and that this processing is what is subject to dual-task interference.

We also discovered that a longer period of STC is required to encode more information (3 characters vs 1 character). This is also an important property of STC because it implies a clear form of capacity limitation. What causes this capacity limitation is not clear at the moment. We consider two alternatives: the STC process could be serial, taking longer as more items are processed because each item is consolidated one at a time, or it could operate in parallel, but with limited capacity such that the total time to complete the consolidation process would be longer as more items were consolidated simultaneously (e.g., Townsend, 1990). In general, it is difficult to determine whether a basic process is serial or parallel. However, it is possible that the new techniques that we have developed to demonstrate STC will allow us to answer this issue in the future. At the moment we note that the increase in RT_2 in the 3-character conditions, at the shortest SOA, was never three times as large as that found for the 1-character condition. However, our efforts to focus on STC, by testing at 350 ms (in Experiments 1–5 and 7), to ensure that sensory and perceptual encoding would be complete, makes it difficult to evaluate the differential average time required to encode 1 vs 3 characters. It seems to us that this is an interesting issue for future research.

We suspect that the time required to perform STC for a word, for example, would be similar to that required for a single letter. The concept of a ''chunk'' (e.g., Simon, 1974) is likely to provide the appropriate unit for predicting STC time. This prediction is under study in our laboratory at the moment. The experiments in this article were designed such that words or meaningful units would be difficult to create, and so we expected that each character would be treated as a separate chunk. This made it possible to measure a longer period of STC when 3 characters were encoded relative to that needed for 1 character.

Choice of Probe Task

In the Introduction we briefly reviewed several articles in which simple response time measures were used as a way to probe for evidence of central involvement of concurrent encoding activities (e.g., Posner & Boies, 1971). In Experiment 5, we used simple RT in $Task_2$, in contrast with the two-alternative discrimination response time task used in all the other experiments. The results obtained with simple RT in $Task_2$ were, in many ways, similar to those obtained with a two-alternative discrimination task. In particular, the mean RT_2 was clearly elevated when 3 items had to be encoded relative to when only 1 item had to be encoded. Furthermore, RT_2 decreased sharply as SOA was increased, as for the two-alternative discrimination version of $Task_2$. There was one result, however, which suggests to us that the two-alternative discrimination procedure was superior to the simple RT procedure: evidence for the STC of a single item, which was clearly evident in the results obtained with the two-alternative discrimination procedure (Experiment 4), was not significant when simple RT was used instead. On the other hand, the simple RT procedure seemed less influenced by possible changes in response preparation as the SOA was increased (see, in particular, Experiment 3), and it seemed to produce curves with relatively sharp temporal profiles, indicating with more precision the SOA at which the results for the 3-character condition reached an asymptote (about 800 ms, as can be seen in Fig. 6a).

It is possible that probes at SOAs of less than 350 ms in Experiment 5 could have allowed us to detect the additional time required for the STC of 1 character. Additional work will be required to determine whether simple RT is as good, better, or worse, than a two-alternative discrimination task as a probe task for the study of concurrent task demands of encoding. Given that the discrimination tasks work well and are less prone to other problems associated with the simple RT task, such as anticipation errors (Schubert, 1996; Van Selst & Jolicœur, 1997), and given that it appeared to be more sensitive to the STC process associated with 1 character (at least with the present choice of parameters), we favor it over the simple RT procedure for the moment (see Pashler, 1994, for additional reasons to prefer choice tasks over simple RT). However, the results of Experiment 5 suggest to us that the simple RT procedure may well provide a useful tool, perhaps with as little further adjustment as a different choice of SOAs.

Choice of Encoding Task

Our goal was to discover whether memory encoding required central mechanisms. To do this we deliberately designed Task$_1$ such that it would primarily reflect the operation of memory encoding (Experiments 1–3, 6, and the encode conditions of Experiment 7). We simply asked our subjects to report what they saw in a visual display, at the end of the trial. We believe that this task provides an opportunity to study a relatively pure process of encoding. In contrast, several other tasks used in the past have made it more difficult to isolate encoding from other processes (letter matching, e.g., Posner & Boies, 1971; Posner & Klein, 1973; Ogden et al., 1980; Comstock, 1973; Johnson et al., 1983; or other multi-component tasks, e.g., Dixon, 1986; Raymond et al., 1992).

Rehearsal, Phonological Recoding, and STC

Is STC simply another name for ‘‘rehearsal’’ (e.g., Craik & Watkins, 1973; Atkinson & Shiffrin, 1968; 1974; Waugh & Norman, 1965)? Rehearsal is a process by which information held in memory is refreshed by recycling the information, such as by repeating the information in one’s head (Baddeley, Lewis, & Vallar, 1984). We do not believe that STC is rehearsal, for a number of reasons. One reason is that the process appears to be completed too quickly to be characterized as a recycling of the information over time. For example, in Experiment 6 in which the subject was to remember 1 letter, the elevation in RT_2 at the shortest SOA was 73 ms, relative to the asymptotic RT_2, and the RT_2 function reached an asymptote at 350 ms, suggesting that central involvement was almost always over by this time. A second reason is that it seems useful to us to distinguish between processes required to achieve the original encoding into memory from those taking place afterwards, such as those required to maintain the information. The costs of ''retention,'' which may indeed be due to rehearsal, are discussed in a subsequent section.

Another reason to doubt that STC is another label for rehearsal is that we had no subjective experience of internally saying to ourselves the name of the letter or symbol, over and over, as we performed the tasks in the various experiments presented in this article. For example, in Experiment 6, we simply did not have any experience of having to repeat to ourselves the name of the one letter that we had to remember until the end of the trial. Yet, the results provide very clear evidence of dual-task interference. We also did not experience inner speech when the task involved reporting whether a letter was an H or an S (Jolicœur & Dell'Acqua, 1996), in an experiment similar to Experiment 6, but in which there were only two possible letters. Yet, in each of these cases, there was clear evidence for dual-task interference of the sort shown in Fig. 8. We also performed several experiments in which the visual stimuli to be remembered were random polygons (new ones on each trial), rather than letters or symbols (Jolicœur & Dell'Acqua, 1997). A pattern of results similar to that found in Experiment 7 was found with random polygons. Although it may be possible to explain the results by appeal to verbal encoding of the visual shapes, and then to the subsequent rehearsal of that information, such accounts seem strained to us. For the moment, we conclude that the best interpretation of the results is that they do not reflect rehearsal. However, it is possible that future research could overturn our conclusion.

A fourth reason to distinguish STC from rehearsal is that the concept of rehearsal was proposed as a mechanism by which information is transferred from short-term memory to a more permanent memory, long-term memory (Atkinson & Shiffrin, 1968). We believe that we are studying the process of encoding information into a form of short-term memory, rather than into long-term memory. We hypothesize that there are at least four basic kinds of memory states. For visual input, the first state corresponds to what we might call iconic memory (Neisser, 1967), and which we called sensory encoding in the Introduction. The second state corresponds with the result of perceptual encoding. Here, representations of object identities are formed and/or activated. Potter (1993) calls this state ''very-short-term conceptual memory'' (CSTM). These representations can remain active only for a short time in the absence of bottom-up support from ongoing sensory activity. Without such support, the output of perceptual encoding decays rapidly and the information is lost. The third state is a form of encoding that is more durable than perceptual encoding representations, which we call durable storage (Coltheart, 1982, 1984). Representations in durable storage can withstand sensory masking and maintain the information over a long time, relative to the duration of unsupported representations produced by perceptual encoding. Finally, the fourth type of representation or state is long-term memory.

Given the short duration of the retention interval, the small amounts of information to be remembered, and the repetition of the material across trials, we think that the most likely form of memory that we referred to as durable storage is a form of short-term memory. Furthermore, the fact that we observed systematic asymptotic costs of retention suggests to us that short-term memory was involved rather than long-term memory. We do not see why maintaining information in long-term memory should require central capacity, whereas holding a memory load in short-term memory is likely to do so (e.g., Logan, 1978). Nonetheless, it is possible that long-term memory mediated some of our results. In this case, our procedure might reflect a consolidation process of information into long-term memory. The degree of long-term memory involvement in our experiments is an issue that we cannot resolve based on the present results alone. We interpreted the evidence as indicative of a process of STC required to encode information into a form of short-term memory, but future work could overturn this conclusion.

In our view, the initial portion of the RT_2 functions of SOA (e.g., Fig. 9a) reflects the process of STC. During this time, representations produced by perceptual encoding are transferred, or consolidated, into a more durable form of memory, durable storage. We observe dual-task slowing of RT_2 even when very little information is to be consolidated (e.g., 1 of 19 letters or 1 of 9 symbols, or the information required to distinguish an H from an S in other experiments not reported in this article). Thus, the STC of even a small amount of information is sufficient to produce dual-task slowing in a concurrent task. These results show that the transfer process itself (what we call STC) is causing interference in concurrent processing, on the assumption that durable storage can hold more than one item (Sperling, 1960). That is, the limitations that we demonstrated in Experiments 1–7 were not caused by limitations in the capacity of durable storage.

Stanners, Meunier, and Headley (1969) performed an experiment that bears some surface similarity to ours. They required subjects to encode information presented visually. The visual information was followed by a noise burst, which was the target signal for a simple RT task. They presented 3 sets of 3 letters (trigrams) to their subjects, who were instructed to remember as many letters as possible. Two different kinds of trigrams were used: easy-to-pronounce and difficult-to-pronounce (Underwood & Schulz, 1960).

Easy-to-pronounce trigrams were exposed for 500 ms while difficult-to-pronounce trigrams were exposed for 5000 ms, in order to equate, roughly, the level of recall of the letters across the two kinds of material. After the presentation of the trigrams, an interval (ISI) of 1, 2, 4, or 6 s separated the offset of the visual display and the onset of the noise signal. In a control condition, the visual material was also presented, but the instructions were to ignore these stimuli and only to perform the simple RT task. Simple RT in the control condition was not influenced by the delay between the visual display and the auditory signal, and the mean was about 230 ms. When the trigrams were to be encoded into memory, simple RT was elevated relative to the control condition and decreased from the shortest (mean simple RT of about 475 ms) to the longest ISI (mean of about 375 ms). Simple RT was also about 75 ms longer for difficult-to-pronounce trigrams than for easy-to-pronounce trigrams.

Stanners et al. (1969) interpreted their simple RT results as a measure of the demands of rehearsal. In their view, simple RT reduced over the retention interval because of a decrease in the ‘‘rehearsal load’’ as information was transferred from primary to secondary memory (Waugh & Norman, 1965). Although we find the results of Stanners et al. (1969) intriguing, several aspects of their procedure make them difficult to interpret. For example, for difficult-to-pronounce trigrams, the three trigrams were exposed for 5 s, and the shortest SOA between the trigrams and the auditory signal was 6 s (while the longest SOA was 12 s). Despite these very long intervals, the simple RTs for this condition had a similar form (as a function of ISI) as those for the easy-to-encode condition (no interaction between pronunciability and ISI in the encode condition). It is possible that at least some of the changes in mean simple RT as ISI was lengthened reflected changes in preparation for the simple RT task. In any case, because the shortest SOA in their experiment was 1 s, we believe that their results did not reflect, primarily, processes involved in encoding into short-term memory (or durable storage).

Another possible interpretation of our results (and perhaps of Stanners et al.'s) is that the dual-task slowing observed in RT_2 is caused by a process of phonological recoding of the information to be remembered. We tried to address this issue by including material that would be difficult to recode phonologically (keyboard symbols). A similar pattern of results was found with these materials relative to what was found with letters, although there were some notable differences. The symbols were more difficult to remember (Figs. 2c, 3c, 4c, and 6b). Response times to the tones were generally longer when symbols were encoded than when letters were encoded. One could interpret the added difficulty of processing the symbols as a reflection of a greater difficulty of phonological recoding for symbols relative to letters. Another difference between the results for symbols vs letters was the interaction between number of characters and SOA. For letters, we found an interaction in Experiments 1, 4, 5, and 7 in which the effects of SOA were larger when 3 letters were encoded than when only 1 letter was encoded. In contrast, for symbols, we found clearcut evidence for a similar pattern of results only in Experiment 5, while additive effects of SOA and number of symbols were found in Experiments 2, 3, and 4.

The results suggest that some aspect of the processing of letters was different from the processing of symbols. If the increase in RT in the tone task was due to a process of phonological recoding, and if this process required more time for symbols than for letters, then one might have expected that a steeper slope in the effects of SOA should have been found for symbols than for letters, because the initial cost of the recoding would have been greater for symbols than for letters. This interaction was not found. Furthermore, the interaction between the number of characters and SOA that was observed for letters should have been even larger for symbols. This prediction is based on the notion that the increase in time to recode the symbols would have been multiplied by some factor in the 3-symbol condition compared with the 1-symbol condition, and that this difference should have attenuated as the recoding process ran to completion at longer SOAs. The fact that a larger interaction was not found for symbols relative to the one found for letters supports our contention that the encoding process we are tracking with RT_2 may not be due to phonological recoding, *per se.* It is likely that work with other kinds of visual information, such as random polygons (Jolicœur & Dell'Acqua, 1997), may help to resolve this issue in the future. At the moment, we leave open the possibility that the evidence we provided in support of STC could reflect a process of encoding such as phonological recoding.

Is STC Necessary for Explicit Memory?

Two aspects of the results suggest that there is no explicit (Nelson, Schreiber, & McEvoy, 1992; Schacter, 1987) memory representation of perceptually encoded information without STC. First, the pattern of RT_2 results in Experiments 4, 5, and 7 is consistent with the view that STC was not engaged when the information that was presented did not need to be remembered. Second, to corroborate the view that STC is necessary for the creation of a representation in durable storage, we asked for recall of information that, by hypothesis, was not subjected to STC (Experiment 4a). Recall level was at or near chance. One thing that is interesting about this result is that the stimuli had to be processed deeply (Craik & Lockhart, 1972) enough to classify the character as either a letter or a symbol. In other experiments with essentially the same results as those obtained in Experiment 4, subjects were instructed to recall letters and ignore digits (Jolicœur & Dell'Acqua, 1998). In that case, the characters had to be processed enough to discriminate letters from digits. Yet, memory for the information that the subject did not try to remember was at chance. The suggestion is that the processing required to categorize characters as either letters, digits, or keyboard symbols does not automatically lead to the creation of a representation in durable storage. The evidence leads us to suggest that STC is necessary in order to create a representation in durable storage. The deployment of STC is under strategic control by the subject such that information is either remembered or not depending on the goals of the subject (Experiments 4, 5, and 7, encode vs ignore conditions). Thus, the creation of representations in durable storage (explicit memory) is not automatic. Furthermore, the results suggest that the STC process that is necessary for the creation of a representation in durable storage requires capacity-limited central mechanisms that are also required for such cognitive operations required to perform a simple concurrent task, such as response selection in the tone task. The arguments concerning the necessity of STC for storage in durable storage are subject to the caveat that we formulated earlier concerning our test of recall for ignored information (see Experiment 4a).

Central Demands of Retention

We observed a number of results suggesting that the maintenance of information in durable storage produced some dual-task slowing (see also Logan, 1978). It seems likely that retention, per se, requires some central involvement. When only 1 character had to be remembered, however, these ''costs'' of retention appeared to be rather slight (see Figs. 4a, 6a, and 9a). Costs of retention appeared to be more significant when more information had to be remembered (i.e., encode-3 condition vs encode-1), and perhaps when the information was less over-learned (i.e., symbols rather than letters). The best evidence for this notion was that the mean RT_2 for 3-character conditions remained longer than that for the 1-character condition, even at the longest SOAs in every experiment where this comparison is possible. At these very long SOAs we expect that all the information was already encoded into durable storage; if so, differences in RT_2 were probably due to retention.

It is possible that differential central demands of retention for letters vs symbols could explain why the manipulation of number of characters and SOA tended to interact more strongly for letters than for symbols. The suggestion is that for letters, the greater cost of encoding 3 characters relative to that for 1 character was clearly visible in the interaction between SOA and number of characters. Furthermore, the increase in RT_2 associated with the retention of 3 letters was probably quite modest. This allowed the RT_2 function of SOA for the 3-letter condition to come down to an asymptote that was nearly the same as that for the 1-letter condition (e.g., only 21 ms difference in Experiment 1). For symbols, in contrast, this effect may have been masked by a growing cost of retention as SOA was increased, especially when there were 3 symbols to remember. This increase in retention load would have prevented the RT_2 function of SOA in the 3-symbol condition from coming down to the same asymptote as for the 1-symbol condition.

It is clear that a complete characterization of the results produced by the paradigm used in the present article will require a consideration of the effects associated with the retention of information, especially when three or more objects (or chunks) are to be remembered. We return to this issue in a subsequent section of the General Discussion.

A Model of Task Interactions

In Fig. 10 we present a model of task interactions that can account for several aspects of the response time results in the auditory task used in this article. This model assumes that the interference between tasks results from the postponement of a stage of processing in the tone task. Another possibility is that one or more stages of processing in the tone task were slower when concurrent processing occurred (as SOA was reduced). For ease of exposition we will describe the interference in terms of postponement, but the reader should keep in mind that the present results do not allow us to distinguish this form of interference from capacity sharing. The model illustrated in Fig. 10 could easily be modified to model a capacity sharing form of interference by replacing postponement by a graded slowing of processing in one or more stages of processing in the tone task (e.g., slowing in the response selection stage).

We focus on effects of STC in the type of design that we used in Experiment 4. For the moment we neglect effects on Task$_2$ due to retention, but we will return to this issue in the next two sections of the General Discussion. In Experiment 4, the subject first had to determine whether the visual information was to be remembered or not, the quantity of information was varied, and a tone was presented at various SOAs following the visual display. We hypothesize that STC requires central mechanisms that are also required to select a response. Figure 10a represents the task interactions for the encode condition when 1 character was encoded. First, the visual characters are subjected to sensory encoding (SE in the model in Fig. 10) and perceptual encoding (PE in Fig. 10) operations. Experiments 1–5 and 7 were designed to maximize the likelihood that the dual-task slowing phenomena that we demonstrated in this article would be due to STC rather than to earlier encoding operations. We selected SOAs that made it very likely that sensory and perceptual encoding processing had finished by the time the tone was presented. Furthermore, for sensory encoding, at least, we expect that central mechanisms are not required. Whether central mechanisms are required for perceptual encoding, in the general case, is more controversial, as can be gleaned from work in the PRP literature (contrast De Jong, 1993 and De Jong & Sweet, 1994, with Pashler, 1989). We expect that perceptual encoding can sometimes be achieved without central processing, whereas in other cases, central processing may be required (McCann & Johnston, 1992). It is for this reason that, in most of the experiments, we allowed a relatively

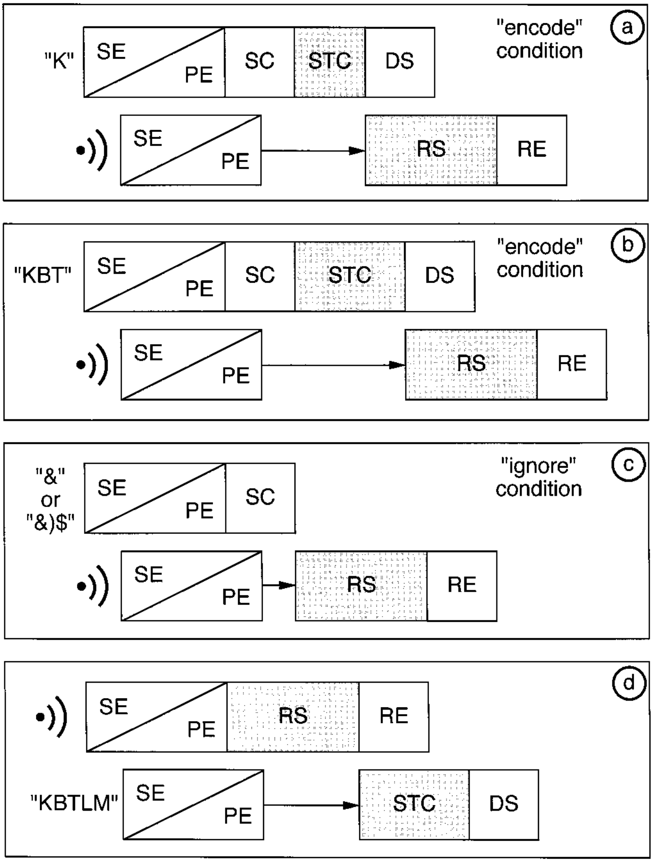

FIG. 10. Model of task interactions. In panels a–c, visual information is presented first (top stage diagram in each panel) followed by a tone (bottom stage diagram in each panel). (a) Model for the encode-1 conditions of Experiment 4. In the visual task, following early encoding operations—sensory encoding (SE) and perceptual encoding (PE)—selective control (SC) operations evaluate the visual information, determine that it should be selected for memory encoding, and pass this information to short-term consolidation (STC) processes. STC creates a copy of the information produced by PE in durable storage (DS). SC and STC require central mechanisms. While SC and STC processes are engaged, response selection (RS) in the auditory task must wait. (b) Model for the encode-3 conditions of Experiment 4. STC for 3 objects takes longer than for 1 object (panel a). (c) Model for the ignore conditions of Experiment 4. SC operations determine that the visual information can be ignored. Therefore, STC is not engaged. RS for the auditory task waits only a short time. (d) Here, a tone is presented first (top stage diagram), and is followed by a visual display (bottom stage diagram). The auditory task gains access to central mechanisms first, and RS for the tone task occupies these mechanisms for a period of time. While central mechanisms are busy with RS in the auditory task, STC in the memory task is delayed. During the period of delay, PE representations of the visual information decay if the visual display is followed by a pattern mask.

long time to elapse before presenting the stimulus for $Task_2$. We believe that this allowed us to focus on the potential central involvement of STC without the involvement of perceptual encoding.

Following sensory and perceptual encoding (Fig. 10a), the information must be evaluated to determine whether it should be remembered or not. Information that should be remembered is selected for further processing. We refer to the processes that perform these operations as ‘‘selective control’’ (SC in Fig. 10). For information that should be remembered, letters in the example shown in Fig. 10a, selective control processes send the visual information to an additional process of short-term consolidation (STC). We hypothesize that STC is necessary in order to create a representation in durable storage (DS in Fig. 10). While selective control and STC operations are performed on visual information, response selection (RS in Fig. 10) for the auditory task must wait (or slows down). As the SOA is reduced, the probability that response selection for the auditory task has to wait increases, and the period of waiting becomes longer, on average. This period of waiting is observed as an increase in RT_2 as SOA is decreased. These effects are not seen at longer SOAs because selective control and STC will have finished on most trials. These postulated interactions explain the effects of SOA observed in the encode conditions of Experiments 1–7. In Experiments 1–3, 6, and 7, the duration of selective control is either very short or nil because every perceptually encoded representation arising from the visual display could be sent directly to STC (or ignored without an on-line decision in ignore blocks of Experiment 7). It is probable that there is either no or very little separate cost of selective control in this case. The very small effects of SOA in the ignore condition of Experiment 7 are consistent with this suggestion. However, there could be a general cost associated with maintaining the cognitive operations required to perform STC in a state of readiness (Rogers & Monsell, 1995).

Figure 10b illustrates the condition in which 3 characters had to be encoded. The principal effect of the manipulation of the number of characters (in the encode condition) is to lengthen the duration of STC. The longer period of STC produces a longer period of postponement of response selection (RS), which explains the effect of the amount of information on RT_2. The results also suggest that the duration of selective control is likely slightly *shorter* in the 3-character than in the 1-character condition (see Fig. 4a, ignore conditions); but this is not represented in Fig. 10.

Figure 10c illustrates the task interactions for the ignore condition in Experiment 4. In this case, processing in the visual task essentially ends when selective control processes determine that the information does not need to be remembered. We hypothesize that selective control requires central mechanisms, such that while selective control (SC) processing is engaged, response selection (RS) in the auditory task must wait. This waiting period will be shorter, however, than in the encode conditions because an additional period of STC is required in the encode conditions. This hypothesis thus predicted that a significant effect of SOA would be found even on ignore trials of Experiment 4 (and 5). If the need to decide whether information should be encoded or ignored is eliminated from the task, then information that can be ignored should not elevate RT_2 even at short SOAs. The results of the blocked ignore condition in Experiment 7 confirmed this prediction of the model.

The most important assumption of the model illustrated in Figs. 10a–10c is that STC requires central mechanisms that are also required to perform operations like selecting responses (RS). While STC is taking place, operations like response selection (RS) must wait (or slow down). This model leads to an interesting prediction, which is illustrated in Fig. 8d. In the experiments presented in this article, the information to be encoded was presented first, followed by an auditory stimulus. Suppose that the order of the stimuli was reversed, but that the subject was still asked to respond as quickly as possible to the tone. As shown in Fig. 10d, we now expect that the processes required for the tone task would engage central mechanisms first (most likely to perform response selection, as shown in the figure). This has a consequence for the processes mediating performance in the memory task. Following early encoding operations, STC would normally begin. However, at short SOAs, central mechanisms are likely to be busy with the operations required to select a response in the auditory task. Thus, at short SOAs, STC will likely not be engaged immediately; STC has to wait for response selection for the tone task to finish. The likelihood that some waiting occurs increases and the mean duration of waiting increases as SOA is decreased.

Suppose that the visual display was masked. Under these conditions, we hypothesize that the representations produced by perceptual encoding decay rapidly (see Introduction, and Potter, 1993). A longer period of postponement of STC should result in more decay of perceptual-encoding representations. This, in turn, should produce a lowering of recall performance in the memory task. While this approach has received some attention in the literature, it typically has been examined in the context of complex task, such as visual search (Pashler, 1989; De Jong & Sweet, 1994). Previous results in the literature have not resulted in a consensus. Recently, Jolicœur and Dell'Acqua (1996, 1998) tested the predictions derived from the model shown in Fig. 10d using a simpler memory task. The memory task was to encode and recall later (without speed pressure) as many characters as possible from a masked visual display containing 5 letters (see Fig. 10d). The auditory task was the same speeded two-alternative pitch discrimination used in Experiments 1–4 and 6–7 in this article. However, the auditory signal was presented first. As the SOA between the tone and the visual display was reduced, recall of the visual information decreased, as predicted by the model illustrated in Fig. 10d. Several aspects of the results were consistent with the model. Lower recall was associated with a more difficult auditory task that was postulated to engage central mechanisms for a longer time (four-alternative discrimination vs two-alternative discrimination). Furthermore, within any given task, longer response times to the auditory signal were associated with lower recall. This result is predicted if we assume that longer response times tend to be associated with a longer period of response selection (Pashler, 1994), which would create a longer period of central postponement of STC. Both of these effects were exacerbated by reducing the SOA between the tone and the visual display, as predicted by the model. These results provide very strong converging evidence with those presented herein in supporting our claim that STC is required for encoding information into durable storage and that STC requires central processing.

Detailed Aspects of the Results Reconsidered

The model presented in the foregoing section and Fig. 10 was intended to provide a ‘‘first approximation’’ explanation of the results presented in this article. Clearly, however, there are numerous unresolved issues and several details of the results that require further consideration. We address some of these issues in this section.

We begin this section with an idealized representation of the results of Experiment 7. The observed results are shown in Fig. 9 and a schematic representation of idealized results is shown in Fig. 11. The figure includes three idealized functions; one for the ignore condition, one for the encode-1 condition, and one for the encode-3 condition. There are eight aspects of the results that are indicated by labels in boxes in Fig. 11. Each of the encode conditions has four key aspects. The first is the cost of encoding at the shortest SOA. These are labeled ‘‘Short SOA Cost 1,’’ for the encode-1 condition, and ‘‘Short SOA Cost 3,’’ for the encode-3 condition. The second is the slope of the steep portion of the functions of SOA; they are labeled ‘‘Slope 1’’ and ‘‘Slope 3’’ in Fig. 11. To simplify the figure and discussion we represented the idealized steep portions of the results as linear functions. In general, however, the results are likely to be nonlinear monotonic decreasing functions (as found in the encode-3 conditions of Experiments 1–5 and Experiment 7). The results of Experiment 6, however, suggest that linear functions may be observed under some conditions.

The third feature of the results is the point at which the steep portion of each function reaches an asymptotic RT. This point is labeled ‘‘Inflection 1’’ for the encode-1 condition and ‘‘Inflection 3’’ for the encode-3 condition. The fourth aspect of the results is the asymptotic difference between each of the encode conditions and the ignore control condition. This difference is labeled ‘‘Asymptotic Difference 1’’ for the encode-1 condition and ‘‘Asymptotic Difference 3’’ for the encode-3 condition. In addition to these eight aspects of the results, a ninth aspect concerns the potential effects of SOA in the ignore condition. This ninth aspect is not included in Fig. 11 to reduce clutter.

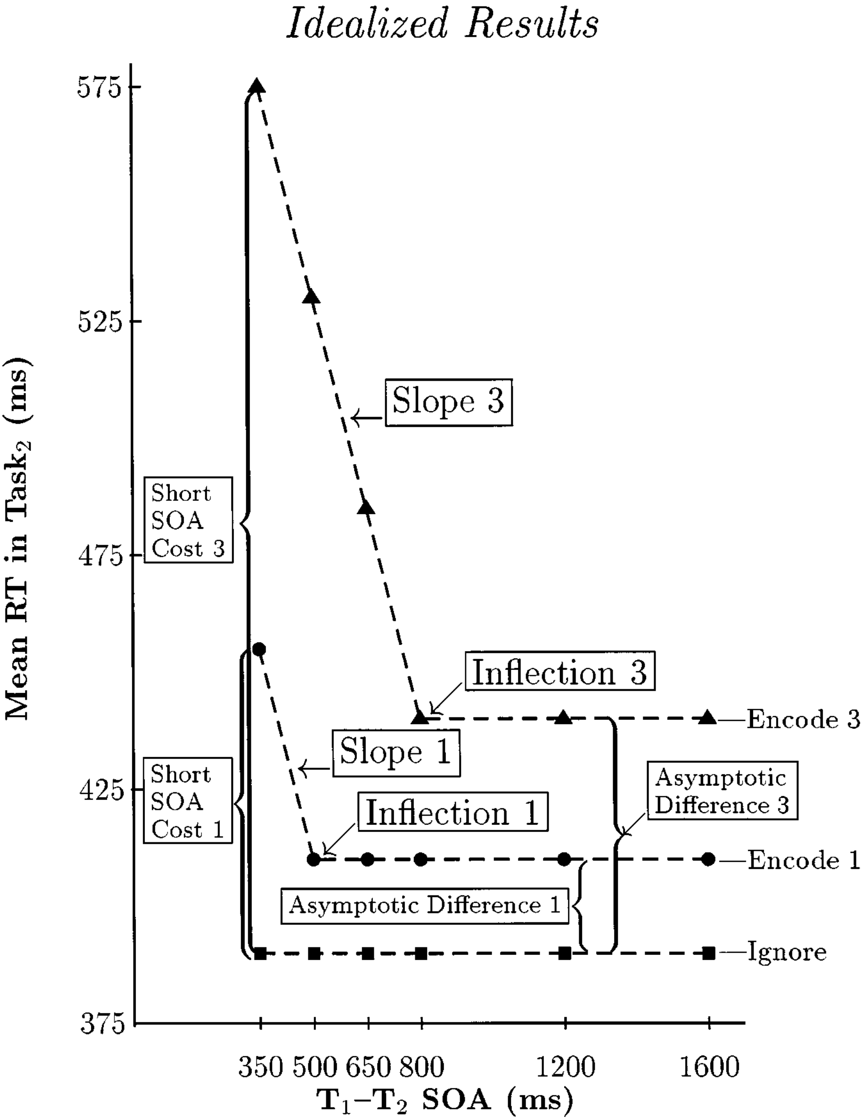

FIG. 11. Idealized results showing effects of SOA, information load, and encoding.

The model we presented in the foregoing section attempts to explain each of the eight key aspects of the results, as well as effects of SOA in different types of ignore control conditions. We already discussed the effects of SOA in the ignore condition in some detail in the foregoing section, and we do not go into further details here. In this section we assume that the ignore condition used the blocked procedure used in Experiment 7, which produced very flat effects of SOA.

Let us now consider each of the eight features of the results illustrated in Fig. 11. Consider first the dual-task costs observed at short SOA. According to the model, encoding information into durable storage requires short-term consolidation (STC) and any period of STC should produce some interference on processing in Task$_2$. Thus, even when there is only one item to be encoded, some dual-task interference should be observed in the response times in Task$_2$. This cost is observed in the results as the increase in RT$_1$ labeled ‘‘Short SOA Cost 1.’’ The larger cost for the encode-3 condition, labeled ‘‘Short SOA Cost 3’’ is expected if a longer period of STC is required when there is more information to be encoded. According to a postponement account of the observed dual-task slowing, the magnitude of the short SOA costs should be functionally related to the mean duration of postponement.

Now consider the slope of the functions. We note that the slopes were considerably shallower than -1 in all seven experiments. A slope of -1 is expected in a postponement account if the magnitude of the postponement is large relative to the variance of the distribution of Task$_1$ stage durations at and before the stage of processing that is causing the postponement. This property of postponement models is discussed in Pashler’s (1994) review of the PRP literature and has been observed at short SOAs in several dual task experiments in which both responses are speeded (Pashler, 1994). Slopes of less than -1, however, are not inconsistent with postponement accounts, as will be demonstrated in the section devoted to computer simulations of our results. A slope of less than -1 is produced when the distribution of stage durations of one or more stages at, or before the bottleneck, has a high variance relative to the mean termination time.

Another way in which a slope of less than -1 can be produced is if the dual-task interference causes a slowing of Task$_2$ processing rather than pure postponement. In this case slopes of less than -1 can be produced by different degrees of slowing associated with the dual-task interference. More slowing would result in a steeper slope whereas less slowing would produce a shallower slope, but all slopes would be less than -1.

There are, therefore, at least two interpretations of the relatively shallow slopes of the steep portions of the dual-task interference curves. One is that there was postponement of Task$_2$ processing by one or more stages of processing required to perform Task$_1$, and that one of these stages had relatively high variance. The other is that the dual-task slowing was not caused by a pure postponement of Task$_2$ processing, but rather by a slowing of one or more stages of processing required to perform Task$_2$. The present results do not allow us to distinguish between these two possibilities.

The third aspect of the results is the SOA at which the steep portion of the curve reaches asymptote. These points of inflection are labeled ‘‘Inflection 1’’ and ‘‘Inflection 3’’ in Fig. 11. We assume that anywhere prior to the point of inflection (i.e., at shorter SOAs), there must have been some interference (either postponement or slowing) of Task_2 processing by Task_1 processing on at least some trials. The point of inflection indicates the SOA at which the probability of such interference approaches zero. The inflection point thus indicates the longest duration of Task_1 stages at or prior to the last stage of processing that can interfere with processing in Task_2. This is true regardless of the form of the interference (postponement or graded slowing), or of the specific assumptions about which processes caused the dual-task interference. Our results are quite interesting in this respect because they show that some interference can be measured even at rather long SOAs, especially when three items had to be encoded. These effects are either not found (Experiments 7) or found only at very short SOAs (Experiments 4–5) when the information does not need to be encoded. The results suggest strongly, therefore, that encoding processes have a rather high variability. Results in the attention blink (AB) literature are also consistent with the suggestion that the encoding information in durable storage is a process whose duration has a high variance because evidence for dual-task interference can often be found 500 ms or more following the presentation of a single item that must be encoded for later report (e.g., Chun & Potter, 1995; Raymond et al., 1992; Duncan, Ward, & Shapiro, 1994; Jolicœur, 1998).

According to the model presented in Fig. 10, the inflection points place an upper bound on the duration of processing up to and including STC, but they tell us little about the mean duration of STC. Thus, like the slope of the functions, the inflection points inform us about aspects of the distribution of the stage durations other than the mean (i.e., the variance). The point of inflection should be at a longer SOA for the encode-3 condition than for the encode-1 condition on the assumption that the longest duration of STC in the encode-3 condition should be associated with higher variance than in the encode-1 condition. This result was observed in Experiments 1, 4, 5, and 7.

The model also makes the prediction that the points of inflection should also have been pushed to longer SOAs in Experiment 4 relative to those observed in Experiments 1 and 7. In Experiment 4, according to the model shown in Fig. 10, a decision to encode or not to encode was made before the information was subjected to STC (in the encode condition). This decision process was not required in Experiments 1 or 7, which used blocked encode trials. The duration of the additional decision processes in Experiment 4, called 'selective control' (SC in Fig. 10), would add both to the mean and the variance of Task_1 stage durations, which should move the points of inflection to longer SOAs. This prediction of the model was confirmed by the results (compare Figs. 1 and 7 vs Fig. 4), especially those for the encode-1 condition for which the inflection point is more easily identified. Note that the comparison across these experiments is complicated by the fact that symbols were used for half of the subjects in Experiment 4, whereas letters were used in Experiment 1 and 7. However we also plotted the results of Experiment 4 separately for letters and symbols, and found that the points of inflection were shifted towards longer SOAs for the letters group, relative to those observed in Experiments 1 and 7 (Fig. 5). Thus, it is likely that the longer inflection SOAs in Experiment 4 were caused, at least in part, by the added decision processes rather than only because of the difference in materials.

In Experiment 6 we observed a shorter inflection SOA (350 ms) than for the encode-1 conditions of Experiment 1 and 7 (500 ms). We do not know why this happened. One possibility is that presenting a single letter on every trial (Experiment 6) reduced the total processing requirements of the task compared to when different numbers of letters could be presented on different trials (as in Experiments 1 and 7). Perhaps the intermixed trials added variability to the encoding processes, which was reflected in the results as a longer inflection SOA. Another possibility is that the inclusion of trials in which three characters had to be encoded may have caused greater proactive interference to build up during the course of the experiment, which would be observed as a longer and more variable duration of STC.

Finally, the fourth aspect of the results is the asymptotic difference between the encode conditions and the ignore control condition. According to the model illustrated in Fig. 10, the two encode functions should converge to a common asymptote, which should be equal to the mean RT in the ignore control condition. Clearly, however, this pattern of results was not observed in our results. Instead, the asymptotic differences depended on the size of the memory load. The model shown in Fig. 10 must thus be augmented with the assumption that some dual-task slowing is associated with maintaining information in durable storage, and not only with the encoding process. As can be seen in Figs. 1–7, however, the amount of asymptotic slowing tended to be modest, especially when the visual stimuli were letters. The asymptotic costs were larger when the visual stimuli were symbols (e.g., Experiments 2–3). The assumption that some asymptotic dual-task slowing should be associated with holding a memory load is entirely consistent with numerous previous articles that have measured response times in speeded tasks while a memory load was maintained in short-term memory (e.g., Logan, 1978; Shulman & Greenberg, 1971; Shulman et al., 1971; Stanners et al., 1969; see also Pashler & Carrier, 1996).

The results of Experiments 1 and 4–7 are all very well captured by the above considerations. The results approximated the idealized functions shown in Fig. 11 to a reasonable degree in each case. In particular, the curves for the encode conditions tended to converge at longer SOAs, except for the asymptotic differences attributable to memory-load effects, as required by the augmented model. In Experiments 1, 4, 5, and 7, this convergence produced highly significant interactions between SOA and the number of items to be encoded.

In Experiments 2–3, however, we did not observe the same convergence between the encode-3 and encode-1 conditions, nor did we find it for symbols in Experiment 4. We do not know why this occurred, especially given that some evidence for convergence was observed for symbols in Experiment 5.

There are some suggestions in the results, however, that may provide useful leads for future research on this issue. One finding was that the asymptotic difference between the encode-1 and encode-3 conditions was larger in Experiments 2–3 (71 ms in Experiment 2 and 54 ms in Experiment 3) than in Experiment 1 (20 ms). It is possible that the larger asymptotic difference reflects a larger cost of maintenance for information that is not as well practiced (i.e., symbols, in contrast with letters). A larger cost of holding information in durable storage would tend to obscure the convergence between the functions because as the costs of STC would decrease over time (because the encoding process was completed), the costs of holding the information in durable storage would increase correspondingly over the same period of time. The cost of holding the information increases as time passes because the amount of information to be held in durable storage increases over time. Initially, we assume that there is no information from the display in durable storage. As time passes and STC processes transfer the information into durable storage, the amount of information in durable storage increases. Thus, the cost of holding the information in durable storage should also increase over time and reach a maximum when all of the information available for transfer has been encoded into durable storage. From this point on, however, the cost of holding the information would remain constant (on the time scales of the experiments in this article). It seems likely, therefore, that the best evidence for convergence would occur for material that is easier to hold in durable storage, and perhaps it is for this reason that we found consistent convergence when we used letters as the visual stimuli, but not when we used symbols (except in Experiment 5). Clearly, this is an issue that will require further empirical investigation.

Computer Simulations

In this section we describe some computer simulations designed to demonstrate that reasonable approximations to the observed response time results in Task_2 can be obtained from specific instantiations of the general model illustrated in Fig. 12. In particular, we wanted to show that slopes of less than -1 in the response times can be obtained in a model in which short-term consolidation causes pure postponement of a stage of processing in Task_2. We do not wish to make a strong claim concerning the nature of the interference on tone RT by STC based on the results of the simulations. The purpose of the simulations is to demonstrate that a postponement model can, in principle, provide a reasonable account of the results. Clearly, these demonstrations do not rule out other possible accounts and additional empirical work will be required to determine the nature of the underlying interference. For the moment, however, we wish to demonstrate that slopes of less than -1 do not rule out a postponement account.

We began with a simulation of the results of Experiment 7. Figure 12 illustrates the key features of the model used in this simulation. There were

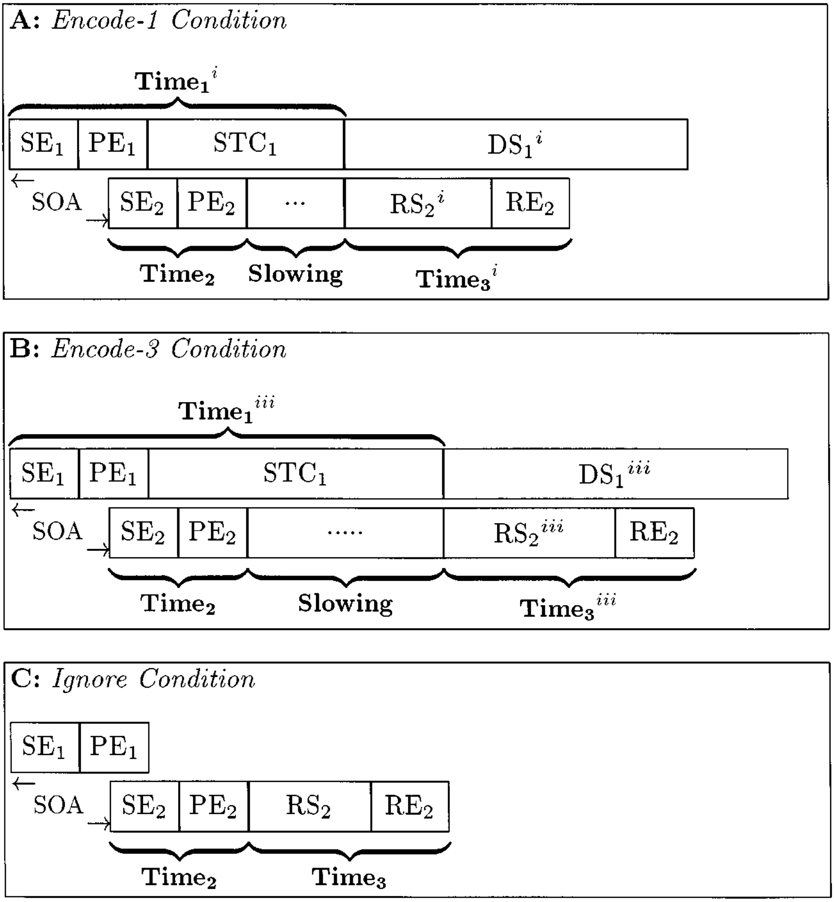

FIG. 12. Model of task interactions used in the computer simulations. (A) Model for the encode-1 condition of Experiment 7. The total duration of SE_1, PE_1, and STC_1 is represented by $\text{Time}_1{}^{i}$, a random variable with an exponential distribution with parameter $\tau_1{}^{i}$. Time_2 represents the combined durations of SE_2 and PE_2. $\text{Time}_3{}^{i}$ represents the combined durations of $RS_2{}^{i}$ and RE_2. STC_1 postpones $RS_2{}^{i}$, causing a period of waiting labeled ‘‘Slowing.’’ $RS_2{}^{i}$ is longer than RS_2 (panel C) because it is performed while a memory load of 1 item is held in durable storage ($DS_1{}^{i}$). (B) Model for the encode-3 condition of Experiment 7. $STC_1{}^{iii}$ is longer than $STC_1{}^{i}$ (panel A) because 3 items must be consolidated. $\text{Time}_1{}^{iii}$, a random variable with an exponential distribution with parameter $\tau_1{}^{iii}$. $RS_2{}^{iii}$ is longer than $RS_2{}^{i}$ because it is performed while a larger memory load (3 items) is held in durable storage ($DS_1{}^{iii}$); thus, $\text{Time}_3{}^{iii}$ is longer than $\text{Time}_3{}^{i}$ (panel A). (C) Model for the ignore condition of Experiment 7. STC is not required in Task_1, and there is no memory load in durable storage. There is no interference across tasks, and RT_2 is just the sum of Time_2 and Time_3.

three conditions that needed to be simulated: encode-1 (Panel A), encode-3 (Panel B), and ignore (Panel C).

Consider first Fig. 12A, which shows the stages of processing in the simulation for the encode-1 condition. There were four key variables required to predict RT_2 in any given simulated trial, and they are labeled ''$Time_1^i$,'' ''$Time_2$,'' ''$Time_3^i$,'' and ''SOA,'' in Fig. 12A. $Time_1^i$ represented the duration of the stages of processing before and including the hypothesized bottleneck in short-term consolidation (STC_1). $Time_2$ represented the combined duration of sensory encoding (SE_2) and perceptual encoding (PE_2) in $Task_2$. $Time_3^i$ represented the combined duration of response selection (RS_2^i) and response execution (RE_2) in $Task_2$. SOA was the time interval between the presentation of the letter and of the tone. On many simulated trials, especially when the SOA was short, a period of waiting was created by the hypothetical bottleneck, and this duration is labeled ''Slowing'' in Fig. 12. The simulated response time in $Task_2$, in a given trial, was given by the following equation:

$$RT_2 = Time_2 + Slowing + Time_3^i. \tag{1}$$

The duration of $Task_1$ processing at and before the bottleneck ($Time_1^i$) was simulated using a single exponential distribution, with parameter τ_1^i. A minimum of 20 ms was imposed on duration of $Time_1^i$. The superscript ''*i*'' in all of the above expressions and in Fig. 12 is used to designate the fact that one item had to be encoded in this condition; the superscript ''*iii*'' is used when three items had to be encoded. The amount of slowing was estimated, on each simulated trial, as follows:

$$\begin{aligned} &Slowing = Time_1^i - SOA - Time_2 \\ &\textit{if} \quad Time_1^i - SOA - Time_2 > 0, \\ &\textit{otherwise} \quad Slowing = 0. \end{aligned} \tag{2}$$

In each run of the simulation 10,000 random samples were used to simulate the distribution of the $Time_1$ variable, and this estimate was used to make a prediction about the duration of RT_2 for each of the SOAs in a given simulation.

The encode-3 condition of Experiment 7 was simulated using the model shown in Fig. 12B. There were two differences between this part of the simulation and that for the encode-1 condition (Fig. 12A). First, a different distribution of $Task_1$ stage durations was used, given that we assumed that the duration of STC_1 would be longer when three items had to be encoded than when only one item had to be encoded. The duration of $Time_1^{iii}$ was represented by an exponential distribution with parameter τ_1^{iii}. Second, the duration of response selection in $Task_2$ was assumed to be different than in the encode-1 condition because of the higher memory load in this condition.

This is represented in the model by the longer duration of Time_3^{iii} compared with Time_3^{i}. The following equations were used to represent response times in Task_2 for this condition:

$$\mathrm{RT}_2 = \mathrm{Time}_2 + \mathrm{Slowing} + \mathrm{Time}_3^{iii}, \tag{3}$$

$$\begin{gathered} \mathrm{Slowing} = \mathrm{Time}_1^{iii} - \mathrm{SOA} - \mathrm{Time}_2, \\ \textit{if} \quad \mathrm{Time}_1^{iii} - \mathrm{SOA} - \mathrm{Time}_2 > 0, \\ \textit{otherwise} \quad \mathrm{Slowing} = 0. \end{gathered} \tag{4}$$

The ignore condition was simulated as shown in Fig. 12C. Here we assumed that there was no postponement of Task_2 processing because no information had to be encoded, and no on-line decision to encode or ignore was required because ignore trials were blocked. Furthermore, as can be seen in Fig. 12C, response selection in Task_2 could now be performed in the absence of a memory load, and we supposed that this would result in a slightly shorter duration of Time_3, as illustrated in Fig. 12C. The following equation was used to represent response times in Task_2 for this condition:

$$\mathrm{RT}_2 = \mathrm{Time}_2 + \mathrm{Time}_3. \tag{5}$$

The results from the ignore condition were averaged across the 1-item and 3-item conditions given that these produced very similar results.

There were six parameters in the overall simulation: τ_1^{i}, τ_1^{iii}, Time_2, Time_3, Load^{i}, and Load^{iii}. Load^{i} and Load^{iii} represent the increase in the durations of Time_3 in the encode-1 and encode-3 conditions relative to the ignore control condition, such that

$$\mathrm{Time}_3^{i} = \mathrm{Time}_3 + \mathrm{Load}^{i},$$

$$\mathrm{Time}_3^{iii} = \mathrm{Time}_3 + \mathrm{Load}^{iii}.$$

We fit 18 group mean response times, 6 for each condition, simultaneously using Equations 1–5. Table 2 shows the set of parameters that produced the fit shown in Fig. 13. The observed means are plotted with filled circles joined by solid lines and the results of the simulation are plotted with unfilled squares joined by dotted lines. The simulation captured the most salient aspects of the results and provided a reasonable first approximation.

The most important aspect of this simulation, for our purposes, is the demonstration that slopes of less than -1 can be produced by a postponement model. Therefore, the fact that the observed slopes in our experiments never approached -1 cannot be taken as evidence against a postponement account of these results.

TABLE 2
Estimated Parameters from Simulations of Experiments 4, 6, and 7

	Experiment		
Parameter	4	6	7
$Time_2$	57.75 ms	85.75 ms	53.75 ms
$Time_3$	373.75 ms	331.25 ms	331.25 ms
$Load^{i}$	4.00 ms	3.75 ms	4.75 ms
$Load^{iii}$	57.35 ms	—	21.35 ms
τ_1°	239.00	—	—
τ_1^{i}	304.00	150.00	275.00
τ_1^{iii}	393.75	—	443.75
RMS_{error}	6.9 ms	6.5 ms	5.6 ms

Note. RMS_{error} is the square root of the average squared deviation between the observed and simulated means.

We also created a simulation of the results of Experiment 4. Recall that this experiment involved ignore trials that were intermixed with encode trials in each test session. Therefore, a decision process was required to determine whether the visual information had to be encoded, or whether it could be safely ignored. In Fig. 10 we called these decision processes selective control (SC). The simulation for Experiment 4 was similar to that for Experiment 7, except that the ignore condition now included the possibility of postponement (Fig. 10c). We simulated this postponement process as we did for the

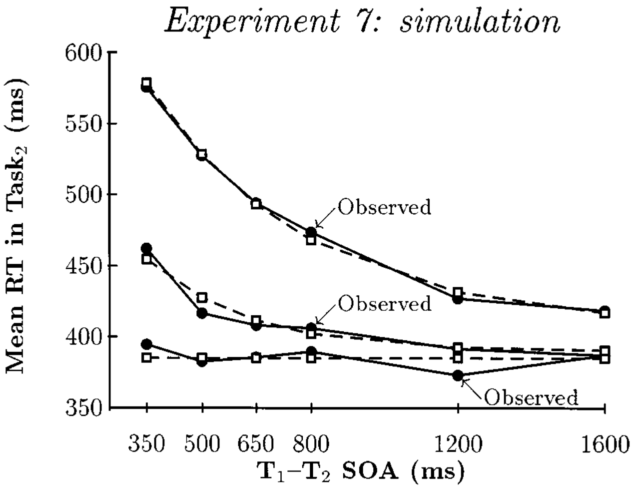

FIG. 13. Results of Experiment 7 (filled circles) and results of the simulation (unfilled squares).

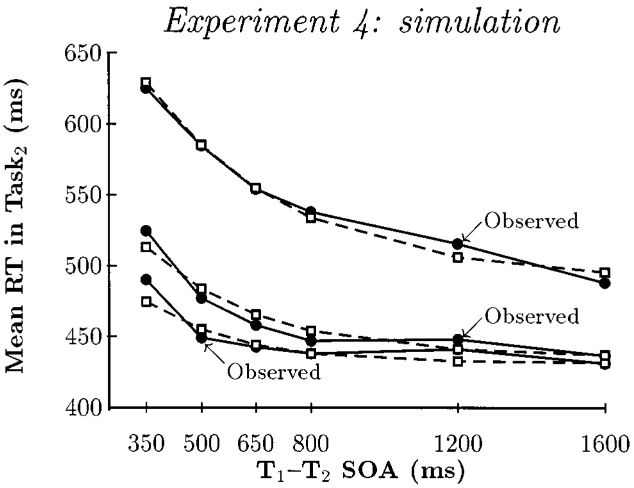

FIG. 14. Results of Experiment 4 (filled circles) and results of the simulation (unfilled squares).

encode conditions, and this required the addition of a new parameter, τ_1°, which was the mean and standard deviation of an exponential distribution of duration times for the sum of sensory encoding (SE_1), perceptual encoding (PE_1), and selective control (SC_1) processing times ($Time_1^\circ$). The following equations were used for the ignore condition:

$$RT_2 = Time_2 + Slowing + Time_3^\circ, \qquad (6)$$

$$\begin{aligned} &Slowing = Time_1^\circ - SOA - Time_2, \\ &\textit{if} \quad Time_1^\circ - SOA - Time_2 > 0, \qquad (7) \\ &\textit{otherwise} \quad Slowing = 0. \end{aligned}$$

Equations 1–4 were used for the encode-1 and encode-3 conditions, with $Time_1^i$ and $Time_1^{iii}$ now representing the sum of the durations of sensory encoding (SE_1), perceptual encoding (PE_1), selective control (SC_1), and short-term consolidation (STC_1).

The set of parameters used to produce the fit shown in Fig. 14 is also shown in Table 2. As for Experiment 7, the simulation provided a reasonable approximation to the results, once again showing that slopes of less than -1 can be produced by a postponement process.

The slope of PRP functions often approaches -1 only at very short SOAs (Pashler, 1994). One might argue, therefore, that only the results of Experiment 6 were truly problematic for a postponement account, because a slope shallower than -1 was observed even at very short SOAs. A simulation of

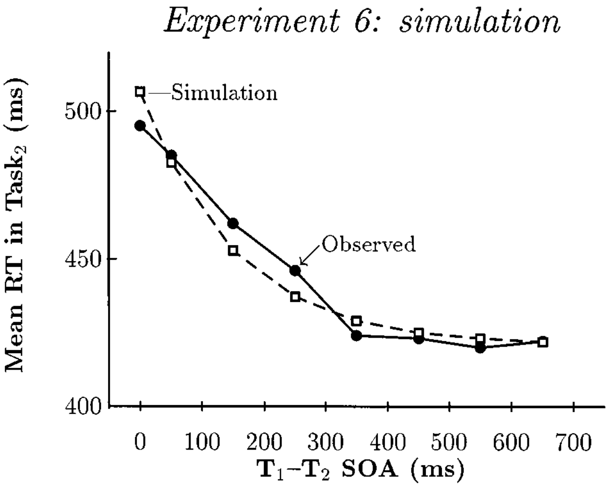

FIG. 15. Results of Experiment 6 (filled circles) and results of the simulation (unfilled squares).

the results of Experiment 6 showed, however, that a shallow slope can be generated in a postponement model even at short SOAs. The simulation used the postponement model and simulation parameters illustrated in Fig. 12A and Equations 1–2. Once again, a reasonable fit of the results could be produced, as shown in Fig. 15, using the parameters shown in Table 2. Therefore, even for very short SOAs, a slope of less than -1 can be produced by a postponement process.

We do not wish to argue that our results and simulations prove that the results we observed were generated by a postponement process or that Task$_1$ stage duration times were exponentially distributed. Our only claim is that a postponement account is not inconsistent with the results. Whether the dual-task interference we observed reflects postponement or a more graded type of slowing of processing in Task$_2$ will need to be addressed in future work. The simulations do show, however, that the models we are proposing can, in principle, produce results that are quite similar to those we observed.

Final Comments

In this article we presented a new paradigm that can be used to study some properties of memory-encoding operations. The paradigm hinges on the discovery that significant dual-task slowing can be observed in speeded concurrent tasks shortly after the presentation of visual information that is to be encoded and remembered for a period of a few seconds (and then recalled, without speed pressure). The dual-task interference effect is sharply attenuated as the SOA between the stimulus in the concurrent task is increased, suggesting to us that the effects observed at short SOA reflect encoding processes. Dual-task costs increased markedly as the amount of information to be encoded was increased, providing further support for our suggestion that the encoding mechanisms are capacity limited. Based on several previous results and theoretical models in the literature (e.g., Coltheart, 1980, 1984; Duncan, 1980; Pashler, 1994; Potter, 1993; Sperling, 1960), we developed a more specific model designed to account for the salient properties of the results (Fig. 12). Computer simulations suggested that the major assumptions of this model are sufficient to provide reasonable approximations to the observed results (Figs. 13–15). In this account, encoding information into durable storage (a form of STM) requires a capacity demanding central process that we called short-term consolidation. While STC is engaged, other operations requiring central processes either must wait or they slow down, allowing us to study the timecourse and capacity demands of STC. The evidence suggested that no explicit memory trace was formed when STC was not engaged (Experiment 4a) and thus that STC may be a necessary operation for the formation of conscious memory representations.

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