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Long-term Repetition Priming of Briefly Identified Objects

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We provide evidence that long-term memory encoding can occur for briefly viewed objects in a rapid serial visual presentation list, contrary to claims that the brief presentation and quick succession of objects prevents encoding by disrupting a memory consolidation process that requires hundreds of milliseconds of uninterrupted processing. Subjects performed a search task in which each item was presented for only 75 ms. Nontargets from the search task generated priming on two subsequent indirect memory tests, a search task and a task requiring identification of visually masked objects. Additional experiments revealed that information encoded into memory for these nontargets included perceptual and conceptual components, and that these results were not due to subjects maintaining items in working memory during list presentation. These results are consistent with recent neurophysiological evidence showing that stimulus processing can occur at later stages in the cognitive system even when a subsequent new stimulus is presented that initiates processing at earlier stages.

It has been claimed that a process of long-term memory consolidation must be applied to perceptually encoded visual objects before a representation in memory is formed that is sufficiently stable to survive the processing of a subsequent event (Potter, 1976; Subramaniam, Biederman, & Madigan, 2000). A critical issue regarding memory consolidation is the amount of time that must be devoted to processing an event for it to be consolidated into long-term memory. Support for the conclusion that consolidation is a slow process has come from behavioral studies that used rapid serial visual presentation (RSVP; Intraub, 1981, 1984; Potter, 1976; Subramaniam et al., 2000). For example, Potter (1976) and Subramaniam et al. (2000) attempted to measure the time necessary for memory consolidation by presenting subjects with a continuous stream of pictured objects. They demonstrated that, particularly with presentation durations shorter than 200 ms, recognition memory performance following list presentation was far worse than immediate identification of those pictures as they appeared within the RSVP streams. Recognition was much improved when longer presentation durations were used, leading Potter and Subramaniam et al. to conclude that pictures are rapidly perceived and identified, but additional processing time on the order of a few hundred milliseconds is required to encode items into long-term memory.

It is not necessary for a stimulus to be in view for several hundred milliseconds in order for the memory consolidation process to lead to successful long-term memory encoding. For example, recognition memory is only slightly impaired when the brief presentation of a stimulus is followed by a blank screen or masked by a picture that is highly familiar and that does not require subjects' attention (Intraub, 1980, 1984). Recognition memory is much more impaired when the brief presentation is followed by a new and meaningful stimulus that initiates conceptual processing, as it is in an RSVP sequence.

Subramaniam et al. (2000) interpreted the neurophysiological findings of Tovee and Rolls (1995) as providing the neural basis for a slow consolidation process. Tovee and Rolls measured the amount of information available in the spike train of single neurons in the inferior temporal cortex of monkeys that responded selectively to faces. They found that enough information to support discrimination between the presented faces was available in the first 50 ms of the spike train, yet the neurons continued to fire for an additional 350 ms. Subramaniam et al. suggested that the additional firing may reflect a slow consolidation process that is disrupted when a subsequent stimulus interrupts processing of the current item, preventing the current stimulus from being encoded into long-term memory.

It should be emphasized that the consolidation

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process we discuss and the process described by Potter (1976) and Subramaniam et al. (2000) involves long-term memory encoding, and is not identical to the slow consolidation process that has been cited as necessary for encoding items into short-term memory (Jolicœur & Dell'Acqua, 1998; Tononi & Edelman, 1998). Accounts of short-term memory encoding are generally agnostic concerning implications for long-term memory. However, the evidence supporting a consolidation process in short-term memory is similar to the evidence for such a process in long-term memory. For example, a consolidation process is used to account for the deficit in reporting a second target in the *attentional blink* paradigm. In a typical attentional blink experiment, subjects are presented an RSVP sequence containing a stream of digits. Two letter targets are inserted in the stream, and the task is to identify both targets. When the second target is presented within 200-600 ms after the first target, recall of the second target is impaired (Chun & Potter, 1995; Raymond, Shapiro, & Arnell, 1992). Furthermore, the attentional blink is obtained despite evidence for extensive perceptual and semantic processing of the second target that occurs outside of awareness, suggesting that encoding a stimulus into short-term memory requires a process beyond identification (Visser, Merikle, & Di Lollo, 2005; Vogel, Luck, & Shapiro, 1998). In contrast, evidence for a more rapid time course of short-term memory consolidation comes from a recent study by Vogel, Woodman, and Luck (2006). In a change-detection task, it was found that approximately 50 ms was needed to encode a pattern into working memory, a much shorter duration than the several hundred milliseconds typically claimed (see also Nieuwenstein & Potter, 2006, for an explanation of the attentional blink without recourse to a consolidation process).

Similarly, a rapid time course for long-term memory encoding is supported by research investigating the long-term influence of a very brief exposure to a stimulus--one that may even occur outside awareness. The *mere exposure effect* was originally demonstrated when subjects made forced-choice preference judgments in which a previously exposed and a completely novel stimulus were paired (Zajonc, 1968). Subjects selected previously seen items at a greater than chance level. In a later demonstration, subjects showed above-chance preference for previously exposed items, even though they had been presented for only 1 ms (Kunst-Wilson & Zajonc, 1980). Likewise, Whittlesea and Price (2001) presented pictures of objects in a long RSVP sequence at 40 ms per item and found that subjects favored items from those sequences over new items, both in a preference judgment task and in a familiarity judgment task in which subjects selected the stimulus that they thought more closely resembled an item from the RSVP sequence. These results are consistent with the view that stimulus exposures below 100 ms are capable of creating long-term memory representations that subsequently influence behavior.

Studies of the mere exposure effect (Kunst-Wilson & Zajonc, 1980; Whittlesea & Price, 2001) are notable in that they include memory tests (e.g., preference judgment) of a form different from those typically used in research on long-term memory consolidation. In fact, one objective of Whittlesea and Price was to examine the common finding that in mere exposure studies there is an effect of previous exposure on preference ratings, but no evidence for memory when subjects are tested with a recognition memory test. The account they provided was not grounded in processing time, but in the strategies subjects employed for different forms of memory tests. Whittlesea and Price described two types of processing strategy: analytic and nonanalytic (see also Chaiken, Liberman, & Eagly, 1989; Jacoby & Brooks, 1984). Analytic processing refers to treatment of a stimulus as a collection of separate features, whereas nonanalytic processing treats the stimulus in a holistic manner. Nonanalytic processing encourages judgments on the basis of feelings of processing fluency which can readily be attributed to preference or familiarity. Previously seen items are likely to be more fluently processed than new items, leading to an advantage for the former. In contrast, when making analytically based recognition memory decisions, subjects attempt to discriminate studied from nonstudied items on the basis of local details. The impoverished encoding conditions of an RSVP list prevent the encoding of such details, leading to discrimination failure when this strategy is applied.

Investigating Memory Consolidation with Direct and Indirect Tests of Memory

The debate presented in this article is not necessarily between a fast or slow memory consolidation process but rather pertains to the question of whether a process beyond initial identification of an item is required to encode that event into long-term memory. We propose that previous failures to find evidence of memory for briefly presented objects were the result of the particular memory tests and procedures used, not the brief duration of the stimuli. The form of memory test typically used when studying memory consolidation has been a recognition memory test, a form of direct test (Intraub, 1981, 1984; Potter, 1976; Subramaniam et al., 2000). It is referred to as a direct test because subjects are explicitly asked to search memory for the probe items and because it can be distinguished from indirect memory tests, in which memory is probed without direct reference to prior experience (Graf & Schacter, 1985; Jacoby & Dallas, 1981; Richardson-Klavehn & Bjork, 1988). An example of an indirect test is the preference rating task used by Whittlesea and Price (2001), in which subjects made a forced choice between a studied and a nonstudied item based on which one they liked more. Subjects were not told that one member of each probe pair had been seen earlier. If subjects show a preference for studied items, then it must be due to their previous encounter with those items, and this preference is evidence that subjects encoded items into memory during presentation of the RSVP lists. Whittlesea and Price reasoned that the brief exposures used in mere exposure paradigms are unlikely to support performance on a recognition memory test because the brief duration severely constrains processing, particularly processing of contextual cues that are important for direct memory tests. But even these brief exposures would engage encoding operations that could later facilitate processing of the items when they reappeared as test probes. Although this processing fluency may not support performance on a recognition memory test, it could serve as the basis for selecting a studied item over a nonstudied item on judgment tasks such as preference or familiarity.

One investigation of memory consolidation employed reasoning similar to Whittlesea and Price (2001) and administered an indirect memory test in addition to a recognition memory test for items presented in RSVP lists. Subramaniam et al. (2000) presented pictures of objects in an RSVP paradigm in which the task was to search for a target specified by presentation of its name in advance of the RSVP list. Lists were presented using item durations of either 72 ms or 126 ms. Critically, because subjects believed the RSVP sequences were part of a search task and not a study phase in preparation for a memory test, they were not motivated to intentionally encode the nontarget items into memory. Rather, the primary task was to identify immediately each item as it was presented to determine whether it was the target designated at the beginning of the trial. On a later indirect test of memory for nontargets, those items were tested in RSVP trials as targets. Subramaniam et al. reasoned that if nontargets had been encoded into long-term memory, then these items should be easier to detect when they later became targets, relative to targets that had not been previously seen in the experiment. They discovered, however, that prior exposure as nontargets failed to improve detection accuracy. In addition, recognition memory for nontargets was not above chance until the item duration on RSVP trials was at least 200 ms. The results from both indirect and direct tests led Subramaniam et al. to conclude that long-term memories were not encoded for items shown for durations less than a few hundred milliseconds.

There is a clear and interesting contradiction between the lack of long-term priming on an indirect test of nontargets reported by Subramaniam et al. (2000) and the evidence for mere exposure effects provided by Kunst-Wilson and Zajonc (1980) and Whittlesea and Price (2001). We suggest that there are methodological and theoretical reasons for the lack of an effect of prior exposure on the indirect test of memory used by Subramaniam et al. First, there is a potential lack of power in their comparison between nonstudied and studied targets. The crucial comparison in their indirect memory test was between two groups of items: (a) search targets that had not been previously presented as nontargets and (b) search targets that had previously been presented one or more times as nontargets. As a result of the experimental design, each subject's accuracy for targets that had not been presented as nontargets (the baseline for measuring the amount of priming) was based on only two trials, whereas performance on targets previously exposed as nontargets was measured with 62 trials. The absence of a priming effect in the search task used by Subramaniam et al. may have been the result of an unreliable measurement of baseline performance (determined by just two trials for each subject). This explanation for the null result reported by Subramaniam et al. receives some support from the fact that, in Figure 1 in Subramaniam et al., the data point representing baseline performance has a much larger standard error of the mean than that for the primed condition.

A second troublesome feature of Subramaniam et al.'s (2000) design was that the two baseline trials were always presented among the first few trials of the experiment. If subjects initially had a relatively low criterion for making a positive detection response but then developed a more strict criterion over the course of subsequent trials, then the detection rate would be artificially high in the baseline condition which would work against finding a priming effect.

Finally, the lack of priming reported by Subramaniam et al. (2000) might have been due to the use of an indirect test that did not entirely conform to the principle of *transfer-appropriate processing* (TAP). This principle holds that a previous experience will influence current experience to the extent that the processing operations applied to both overlap (Franks, Bilbrey, Lien, & McNamara, 2000; Kolers & Roediger, 1984; Morris, Bransford, & Franks, 1977). In the search task used by Subramaniam et al., when subjects encountered a nontarget in an RSVP search list, processing would consist primarily of perceptually driven operations in support of the item's identification. In this case, "perceptually driven" refers to the fact that identification of nontarget objects was carried out in the absence of supporting contextual information (e.g., no verbal label naming the object was presented) such that processing of the object would be based primarily on its perceptual features. When a nontarget item later became a search target, however, the item's name was presented at the beginning of the trial and the subject's task was to actively search for the picture of an object matching that name. This type of search and identification operation would entail a substantial conceptually driven component because the target's identity is known in advance, leading to relatively less reliance on perceptually driven processing to identify the object. Therefore, the processing operations applied to a critical item when it appeared as a target would be somewhat different from those that were used when it had appeared as a nontarget. The TAP literature provides substantial evidence showing that conceptually and perceptually driven operations can be dissociated on indirect tests of memory (e.g., Jacoby, 1983; Weldon & Roediger, 1987), and in particular that priming on a conceptually driven indirect test is weaker when the original encoding episode is based on perceptual rather than conceptual processing (Blaxton, 1989; Srinivas & Roediger, 1990).

In the present study, we attempted to address the design problems and potential violation of the TAP principle inherent in the indirect test used by Subramaniam et al. (2000). We included their indirect test in Experiment 1, but ensured that equal numbers of trials contributed to the baseline and to the primed conditions and that these trials were randomly mixed throughout the test. In all the experiments, we used a masked object-identification task as our primary indirect memory test on the assumption that it would reinstate the initial perceptual identification operations applied to nontargets in the search task without invoking conceptually driven processing. With a more transfer-appropriate indirect test, we expected to obtain a more robust effect of prior exposure. The identification task consisted of a brief, post-masked presentation of a pictured object with the requirement to identify the object. This task makes processing demands that are similar to those invoked during the RSVP lists, namely, the need to visually identify briefly presented, masked objects. Unlike the target detection task of Subramaniam et al., however, there is no search for a predesignated target and therefore no conceptually driven component. Consequently, there should be substantial overlap in the processing operations applied to nontargets during RSVP lists and to the identification of targets in the masked identification task. By the principle of TAP, then, we expect that nontargets from RSVP search lists should show improved performance relative to control items on that task.

Experiment 1

In the study phase, we presented each picture for 75 ms in RSVP format in a visual-search task. The study phase consisted of six trials, and subjects' memory for the items presented as nontargets in these trials was tested using two indirect memory tests. The first indirect test was a replication of Subramaniam et al. (2000). On visual-search trials following the study trials, a nontarget from the study trials could appear as a target for which subjects had to search in the upcoming sequence of pictures. The second indirect test was a masked object-identification task in which subjects were instructed to name isolated pictures of objects shown at a duration that made them very difficult to identify. Some of these pictures had been presented as nontargets in the study phase of the visual-search task and some of the pictures had not been presented previously. If processing of the pictures presented in the visual-search task were preserved in memory, then that experience might facilitate the processing needed to identify these pictures when they became targets in the search task or in the masked object-identification task. We anticipated that the null result reported by Subramaniam et al. would be replicated if the reason for their failure to observe priming was primarily the mismatch of processing operations at study and test. On the other hand, if their null effect was due to the design of their indirect test, then the design we used in constructing a visual-search task as an indirect test of memory should produce evidence of priming. In addition, we expected a priming effect to emerge on the masked identification task.

Method

Subjects. Forty undergraduate students at the University of Victoria participated for extra credit in a psychology course.

Materials. A set of 204 simple line drawings of objects with unambiguous labels (e.g., *cat, anchor, flower*) was selected from Snodgrass and Vanderwart (1980). Eighty of these objects were critical items, and 124 objects were used as filler items. A typical RSVP sequence used in the visual-search task began with six filler items, followed by 20 nontargets, and ending with six additional filler items. If the trial was one in which a search-target was present, an additional target picture was inserted in a random position among the nontarget pictures. In this way, target-present trials included one additional picture in the sequence. A visual mask stimulus was constructed by dividing a complex line drawing into smaller squares and randomly rearranging them to form a jumble of lines. The mask was presented at the beginning and end of each RSVP sequence.

The stimuli for each phase of the experiment were constructed as follows. For the study phase of the visual-search task, 40 of the critical items were randomly chosen for use as nontargets independently for each subject. Six critical lists were created. The nontargets for each list consisted of a randomly selected subset of the 40 critical items. Items were selected for inclusion in these lists such that no item was repeated in a list and each item appeared in three different lists.

Each list was assigned one of six search targets selected from the filler set, and three of the six lists were chosen to be target-present lists.

For the test phase of the visual-search task, 20 of the 40 critical items from the study phase were used as "old" search-targets, and 20 of the unused critical items were used as "new" search-targets. Eighty test lists were created. The 20 nontargets used in each list were selected from a set of 40 filler items such that no item was repeated within an RSVP list, and each item appeared in 40 different lists. Forty target-present lists were created by adding either a new or old critical target to the list. Each of the 40 target-absent lists was assigned a target object name referring to an object that was not included in the list. Finally, two short practice RSVP lists, consisting of 15 items each, were constructed by using items from the filler set. Filler items inserted at the beginning and end of each list were randomly selected with the constraint that no filler was repeated within a list.

For the masked object-identification task, the 20 critical objects from the study phase that were not used in the visual-search test phase were combined with the remaining unused 20 critical objects. Thus, 40 trials were created, and the order of presentation of old and new critical objects was randomized.

Procedure. Subjects were tested individually using a Macintosh G3 computer. Stimuli were displayed in black on a white background. Display of pictures was synchronized with the raster scan of the computer's monitor to ensure accurate control of presentation duration. Subjects sat approximately 40 cm from the monitor, and pictures subtended a maximum vertical visual angle of approximately 6.4° and a maximum horizontal visual angle of approximately 7.2°.

Figure 1A presents a schematic of the experimental procedure. In the study phase, subjects were informed about the nature of the visual-search task. Each trial began with the presentation of the name of the target object (e.g., *apple*), which remained on the screen until the subject pressed a response button. Following the button press, a rapid sequence of pictures of objects was presented in the center of the screen. The task was to decide whether the target object appeared in the sequence of pictures. A row of question marks at the end of each trial signaled the subject to press the "yes" button on a response box if they detected the target or the "no" button if they did not. Subjects were informed that the first two trials were practice lists, and that the subsequent trials would present longer lists of pictures at a faster rate. For the first and second practice trials, objects were displayed for 180 ms and 120 ms, respectively. For the first six critical trials, which constituted the study phase, objects were presented for 75 ms. The objects included in the eighty RSVP sequences constituting the subsequent test phase were each presented for 45 ms to keep performance below ceiling. The 80 test lists were presented in a random order. Although the visual-search task was separated into a study and test phase, subjects were not informed of this fact. Subjects were also not informed that search targets may have been presented previously as nontargets.

Subjects completed a masked object-identification test immediately after the visual-search task. Each trial began with a fixation cross in the center of the screen for 285 ms, followed by a blank screen for an additional 285 ms. A picture of an object was then briefly presented and followed by the visual mask. The mask remained on the screen until the subject provided a name for the object. If subjects could not identify an item, they were encouraged to guess or respond that they did not know. A second computer monitor, visible only to the experimenter, provided the name of the presented object, allowing the experimenter to score the subjects' responses as correct or incorrect. Subjects first completed four practice identification trials, which began with a presentation duration of 240 ms and decreased by 60 ms for each subsequent practice trial. Next, 40 critical trials were presented with the exposure duration initially set at 45 ms. The exposure duration was adjusted over trials, based on the subject's performance on each block of 10 critical trials. The exposure duration was decreased by 15 ms if the subject identified more than eight objects in a block and was increased by 15 ms if fewer than four objects were identified. Importantly, subjects were not made aware of the fact that some pictures in this task had also appeared in the search task.

Results and Discussion

Visual-search study phase. Subjects were generally accurate at detecting the targets in the visual-search task. On average, the proportion of targets correctly detected was .84 (SD = .21) and the false detection rate was .17 (SD = .21).

Visual-search test phase. In the test phase of the visual-search task, the important comparison was between old and new target objects, which would indicate whether previously presenting an object as a nontarget creates a long-term memory representation that facilitates its later identification as a search target. A repeated-measures analysis of variance (ANOVA) revealed that objects that had been presented in the study phase of the visual-search task were correctly detected as subsequent search targets significantly more often than objects that had not been presented (.78 vs. .73), $F(1, 39) = 5.91$, $MSE = .008$. All statistical tests reported in this article use a Type I error rate of .05.

Masked object-identification test. Again, the important comparison was between the old and new objects. Objects that had been presented as nontargets in the visual-search task were correctly identified more

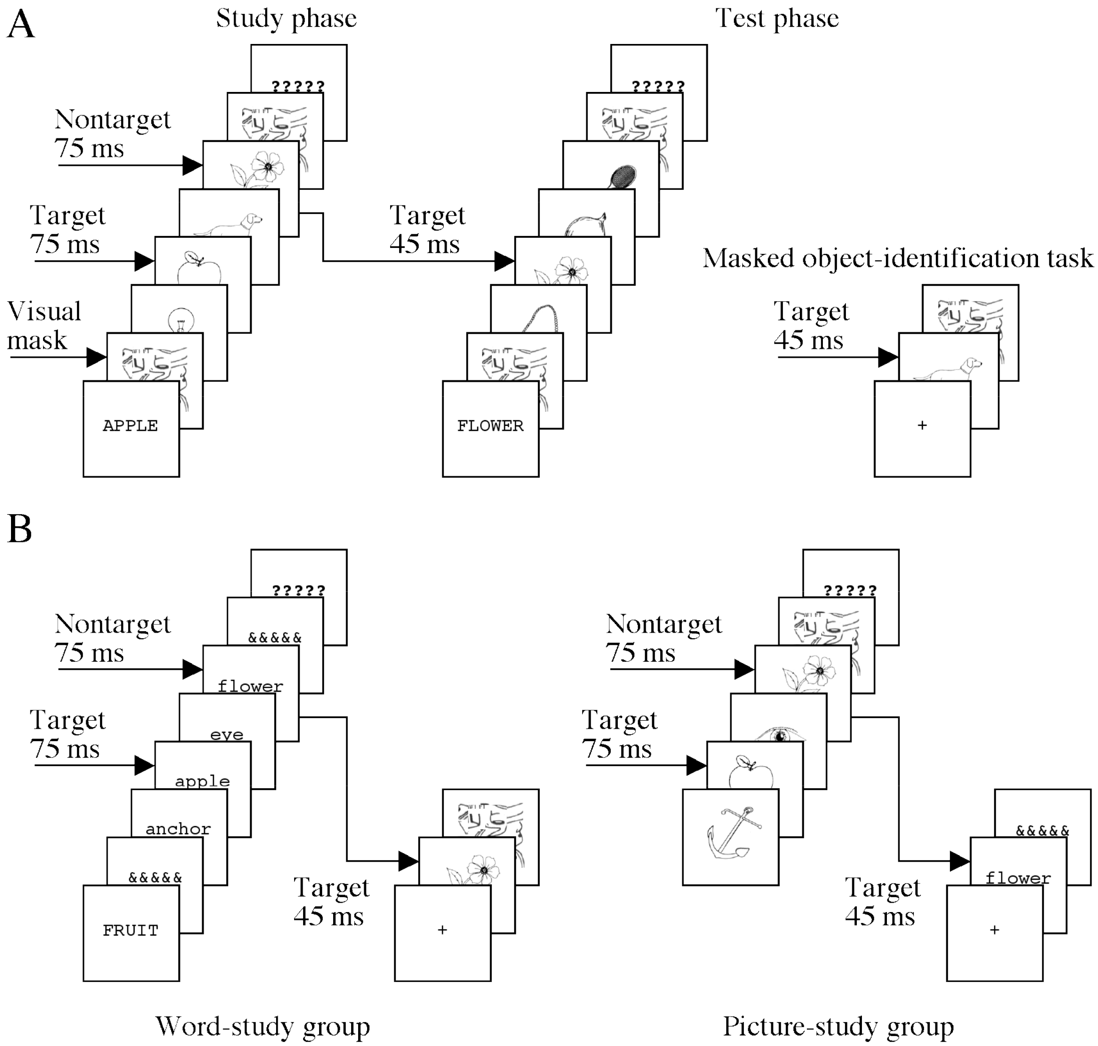

Figure 1. Illustrations of the RSVP visual-search (depicted here with abbreviated RSVP search lists) and masked object-identification tasks. (A) Subjects in the visual-search task determine whether a predesignated target is present in the RSVP list. In the test phase of the search task, as in the final masked object-identification task, some targets appeared as nontargets in the study phase. (B) In Experiment 3, the format of the items was crossed between the search task and the following identification task. Subjects in the picture-study group were presented pictures of objects in the search task but identified briefly presented words in the identification task, whereas subjects in the word-study group were given the reverse order.

often than were objects that had not been presented (.68 vs. .59). A repeated-measures ANOVA indicated that the means were significantly different, $F(1, 39) = 9.96$, $MSE = .017$.

Experiment 1 did not replicate the results of Subramaniam et al. (2000), in that we found that an exposure duration of 75 ms for nontargets was sufficient to facilitate performance when those items later became search targets in the visual-search task. Facilitated performance was also present with an indirect memory test in which subjects attempted to identify single pictures. The results of these indirect memory tests suggest that a duration of only 75 ms in an RSVP search task is sufficient time for subjects to encode information about those objects into long-term memory.

We suspect that it is the difference in the design of our variant of the search task that is responsible for the difference between the outcomes of the present study and that of Subramaniam et al. (2000). Unlike the design of the visual-search task in the Subramaniam et al. (2000) study, we ensured that our primed and unprimed conditions had a substantial number of trials and that these trial types were randomly ordered throughout the test phase. The visual-search task we used retained the mismatch between study and test with respect to the relative emphasis on perceptually versus conceptually driven processing operations, and yet we found a clear priming effect on this test. The size of the priming effect in the search task was somewhat smaller than the priming effect observed in the masked identification task (Cohen's d = .42 versus .67, respectively), so in the remaining experiments we used the identification task in the expectation that it is more likely to produce robust priming effects.

Experiment 2

Having established that long-term memory for object presentations can be formed after very brief identification episodes, the purpose of Experiment 2 was to investigate the nature of the memory representation created by such episodes. Subjects may encode information about the perceptual details of an object and about conceptual knowledge associated with that object, both of which could support performance in the masked object-identification task. In Experiment 2, we examined possible contributions of perceptual information. The study phase was similar to that used in Experiment 1, and the only indirect memory test used was the masked object-identification task. In that test, some of the critical items that had previously appeared as nontargets during visual search were presented as mirror-reversed versions of their original form. If presentation in the visual-search task leads to encoding of perceptual details that contribute to later identification of the object, then modifying the visual form of an object through mirror reversal should interfere with this contribution and reduce performance. Mirror-image reversals, however, share some visual information with their previously presented counterparts, such as spatial frequency, and each is still a depiction of the same conceptual object, so we expected that identification of the mirror-reversed items may still be facilitated relative to objects never presented in the visual-search task.

Previous investigations of long-term priming of mirror reflections of studied pictures have reported mixed results (Biederman & Cooper, 1991; Burgund & Marsolek, 2000; McAuliffe & Knowlton, 2000; Seamon et al., 1997; Srinivas, 1996). For example, in Biederman and Cooper (1991), subjects named simple line drawings in a first block of trials, and named either exactly the same drawing or a mirror image of the drawing in a second block. They found that, relative to naming latency in the first block, both forms of images showed similar facilitation in the second block. Because of high variance associated with naming pictured objects, McAuliffe and Knowlton (2000) predicted that a more sensitive indirect test would show an effect of left-right orientation. Their test task consisted of probe objects appearing initially at a brief duration in a stream of distractors. The duration was progressively increased for each object on later trials until all of the objects had been accurately named. McAuliffe and Knowlton found that original images were named at a shorter average duration than mirror images, which were in turn named at a shorter average duration than pictures in an unprimed baseline condition. It is possible that under test conditions involving degraded visual presentation, as in the present experiment, the physical details of the original experience with an item will have a larger influence on performance, relative to tasks that present a clear view of a target stimulus.

Two variants of Experiment 2 were conducted, one in which subjects searched for a specific object, as in Experiment 1, and one in which they searched for a member of a designated category. We introduced the second type of search target to assess the generality of identification processes that can create long-term representations even with brief exposures. It is possible, for example, that different types of information might be encoded or emphasized if the search task requires one to detect any member of a conceptual category rather than a specific object.

Method

Subjects. A sample of 80 students drawn from the same pool as in Experiment 1 participated in Experiment 2. Half took part in Experiment 2A and half were tested in Experiment 2B.

Materials. The items used in Experiment 2A were identical to Experiment 1, except that 12 critical items from that set that were close to being symmetrical about the vertical axis (e.g., bell, lamp) were replaced with new objects that clearly were not symmetrical. This change was necessary so that objects would be perceptually distinct in their original and mirror reversed versions. Search lists were constructed as in Experiment 1. In Experiment 2B, the critical items were the same as in Experiment 2A except for 20 objects that were replaced to ensure that none of the critical items were exemplars of any of the six search categories that were used (school supplies, fruit, body part, furniture, insect, and musical instrument). For each search category, we selected three exemplars, of which one was randomly selected for each subject. The search lists for Experiment 2B were constructed as in Experiment 1, except category names rather than specific object names were used to define the target on each search trial. For both Experiments 2A and 2B, the items for the masked object-identification task were set up as in Experiment 1, except that all critical items from the RSVP search task were presented in the identification task, as it was the only indirect memory test included. A randomly selected half of the critical items that had appeared as nontargets during the search task were presented in mirror-reversed form.

Procedure. The procedure for both versions of Experiment 2 was identical to Experiment 1, except for

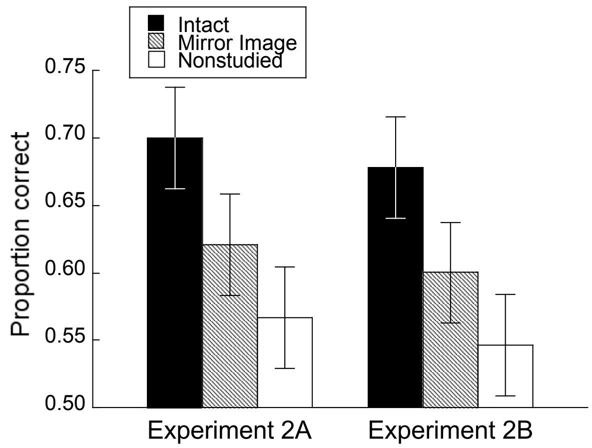

Figure 2. Experiment 2A subjects searched for a specifically named object; in Experiment 2B they searched for a member of a designated category. Error bars are 95% within-subject confidence intervals (Loftus & Masson, 1994; Masson & Loftus, 2003).

the visual-search task instructions for Experiment 2B. In that case, subjects were informed that each trial would begin with the presentation of a category name and the task was to detect the presence of an exemplar from that category.

Results and Discussion

Visual-search task. The mean proportion of correctly detected targets was .81 (*SD* = .26) and .73 (*SD* = .24) for Experiments 2A and 2B, respectively. The corresponding mean false detection rates were .16 (*SD* = .24) and .12 (*SD* = .21).

Masked object-identification test. Mean proportion correct in the identification task was computed for three sets of critical items, intact, mirror image, and nonstudied. The means for each version of the experiment are shown in Figure 2. It is apparent that both variants of the search task led to the formation of memory representations that enhanced later object identification and that this enhancement was reduced by testing objects in mirror-image form. Separate repeated-measures ANOVAs for each version of the experiment confirmed this impression, yielding a reliable effect of item type in each case: $F(2, 39) = 12.90$, $MSE = 0.014$, for Experiment 2A, and $F(2, 39) = 13.28$, $MSE = 0.013$, for Experiment 2B. Planned comparisons were conducted to determine whether mirror reversed objects produced reliable enhancement over new objects and whether that enhancement was equal to that found for intact objects. The pattern of results was the same for Experiments 2A and 2B. Namely, mirror-image objects were more accurately identified than nonstudied objects, $F(1, 39) = 7.63$, $MSE = 0.008$, F(1, 39) = 5.66, MSE = 0.010, but accuracy for mirror-image objects was less than for intact objects, $F(1, 39) = 7.62$, $MSE = 0.016$, $F(1, 39) = 6.62$, $MSE = 0.018$.

The results of Experiment 2 show that identification of briefly presented objects was influenced by the degree of visual similarity to the version, if any, of the tested object that had been seen in the search task. Intact objects and mirror-image objects both represented the same concept that had been experienced in the search task, but intact items were more likely to be identified in the test phase. This outcome suggests that some aspect of the original visual form was preserved in memory. This result was obtained using two different forms of a visual-search task in the study phase, one in which subjects searched for a specific object and one in which subjects searched for the exemplar of a category. The exemplar-search task might have been expected to encourage a greater degree of conceptual processing during search, but sensitivity to changes in visual form was equally strong in both search conditions, as indicated by an ANOVA that treated version of Experiment 2 as a between-subjects factor. This analysis found no interaction between type of search task and performance across the three types of items tested, $F < 1$.

The implications of the benefit found for mirror-image objects over nonstudied objects are somewhat unclear. That benefit could be due to the visual similarity of mirror images to the original forms that had been presented in the search task or to the strong conceptual similarity between mirror versions of the same picture of an object. Either or both of these aspects of mirror-image objects could have generated the priming effect found with these objects in Experiment 2.

Experiment 3

The purpose of Experiment 3 was to determine whether the memory representations formed by nontarget identification during a search task have a conceptual component. We reasoned that if conceptual information about a nontarget was encoded, then that information might support identification of the object when presented in a completely different physical form on a later test. Therefore, in Experiment 3, we changed the format in which an object was presented in the search task and in the masked identification test. Half of the subjects experienced critical nontargets in a search task that presented pictures of objects, just as in the earlier experiments. In the test phase, however, subjects were asked to identify briefly-presented words that were names of objects, some of which they had seen earlier as pictures in the search task. The other half of the subjects were given a search task that presented lists of object names, rather than pictures of objects. They were then tested with pictures of those objects and of objects whose names had not appeared in the search task. Cross-form priming, whereby prior encoding of a pictured object improves later identification of its name, or vice versa, would indicate that subjects encoded conceptual information about nontarget items during the search task.

Evidence for cross-form priming has been inconsistently documented in the implicit memory literature, with small but reliable cross-form priming effects found on verbal implicit memory tasks, such as word fragment completion, in some experiments (Brown, Neblett, Jones, & Mitchell, 1991; Roediger, Weldon, Stadler, & Riedler, 1992; Weldon & Roediger, 1987), although other studies report no significant cross-form priming (Rajaram & Roediger, 1993; Weldon, 1991; Weldon, Roediger, Beitel, & Johnston, 1995). It is likely that cross-form priming is inconsistent because it is a much weaker effect than same-form priming. Small but nonsignificant amounts of cross-form priming were evident in all four of the implicit memory tests examined by Rajaram and Roediger (1993) and the two implicit tests used by Weldon (1991). We therefore anticipated that a small effect of cross-form priming would be found if conceptual information about briefly presented nontarget items in a search list is encoded into long-term memory.

Method

Subjects. Eighty students from the same pool as that used in the earlier experiments participated in Experiment 3. Half of the subjects were randomly assigned to each cross-form priming group, picture study or word study.

Materials. The item set used in Experiment 2B was modified to exclude 12 objects whose names were quite long or were word phrases. They were replaced with new objects so that for all critical items, the commonly used name was between three and eight letters in length. These changes were made so that there would be only a modest amount of variability in word length when words were presented in the search task or in the masked identification task. An additional five objects from the original set were replaced because the object name was ambiguous as to its referent (e.g., *nail* could refer to a nail used with a hammer or to a fingernail). To accommodate these changes in the item set, we also replaced two of the categories used in the visual-search task, resulting in the following six search categories: school supplies, jewelry, body part, furniture, building, and musical instrument. Each category included two exemplars, one of which was randomly selected for each subject, to appear on target-present trials. Apart from these replacements, the RSVP lists in the search task and the masked identification trials in the test phase of Experiment 3 were constructed as in Experiment 1.

The form of the items (pictures vs. words) in Experiment 3 was manipulated such that subjects saw one form in the study phase and a different form in the test phase, requiring two groups of subjects. Subjects in the picture-study group completed a search task consisting of lists of line drawings of objects. For these subjects, the masked identification test involved the presentation of words that were the names of objects. Half of those target words referred to objects whose pictures had been presented in the study phase, and half referred to objects that had not previously been presented as nontargets. Subjects in the word-study group completed a search task comprised of lists object names. In the masked object-identification test, these subjects were shown pictures of objects whose names had or had not appeared as nontargets in the search task.

Procedure. The procedure was identical to Experiment 2B, except for modified instructions regarding the presentation of word stimuli in the search task or the masked identification test. See Figure 1B for a schematic of the visual-search and identification tasks presented to each group of subjects. Subjects in the word-study group were informed that each trial would begin with a category name and their task was to detect the presence of a category exemplar among the sequence of briefly presented words. The masked object-identification test completed by subjects in the word-study group was identical to that used in Experiments 1 and 2, in which subjects named a briefly presented picture. Subjects in the picture-study group completed the same visual-search task as in Experiment 2B, and were instructed in the test phase to identify briefly presented words. Each trial in the masked word-identification test began with a fixation cross and the subject pressed the spacebar to initiate the trial. The fixation cross was followed by a blank screen for 255 ms, followed by the presentation of the target word for 45 ms. The target was immediately followed by a mask for 105 ms, consisting of a row of 8 ampersands (&&&&&&&&).

Results and Discussion

Visual-search task. On average, subjects in the picture-study group correctly identified the target on .78 (*SD* = .24) of the target-present trials and made false positive responses on .24 (*SD* = .26) of the target-absent trials. Detecting a target in an RSVP list consisting of words was relatively more difficult. Subjects in the word-study group correctly identified the target on .45 (*SD* = .32) of the target-present trials and the false detection rate was .21 (*SD* = .28).

Masked identification test. Mean proportions of correctly identified items in the masked identification test are shown in Figure 3. An advantage for items seen

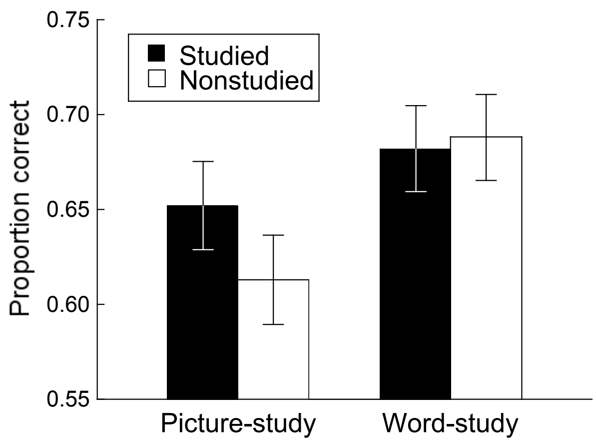

Figure 3. Mean proportion correct in the masked identification test as a function of item type in Experiment 3. Subjects in the picture-study group saw line drawings of objects in the search task and were tested on object names; subjects in the word-study group saw object names in the search task and were tested with line drawings. Error bars are 95% within-subject confidence intervals.

as nontargets in the search task is apparent only in the picture-study group--that is, there was successful cross-form priming when moving from initial exposure to pictured objects to a test in which the object names were presented. Priming was not obtained when subjects initially encoded object names and were later tested with line drawings of those objects. A mixed-design ANOVA was performed on the accuracy scores with group (picture study, word study) and item type (studied, nonstudied) as factors. The analysis revealed no main effect of group, $F(1, 78) = 2.63$, $MSE = 0.112$, and no effect of item type, $F(1, 78) = 2.21$, $MSE = 0.011$. The interaction was significant, $F(1, 78) = 4.02$, $MSE = 0.021$, and planned comparisons were conducted to investigate the source of the interaction. In the picture-study group, subjects were significantly more accurate at identifying words that had been presented as pictures in the study phase relative to words whose pictures had not been presented earlier, $F(1, 39) = 5.83$, $MSE = 0.031$. Subjects in the word-study group were equally accurate at identifying pictures of objects regardless of whether or not the names of those objects had been presented earlier, $F < 1$.

The demonstration of cross-form priming, as defined by exposure to pictured objects facilitating the later identification of their word referents, provides evidence that conceptual information is included in the memory representations formed by the original exposure. An alternative explanation for the presence of cross-form priming in the present experiment is that subjects might covertly name each picture during the search task, thus encoding the name of the picture into memory. Encoding the name would then produce facilitation for the picture-study group when they attempted to identify the object names in the masked identification task. Weldon and Roediger (1987) provided evidence that this is an unlikely cause of cross-form priming by showing that manipulation of the degree to which subjects were motivated to engage in picture naming at study was unrelated to the amount of priming for the picture labels in the subsequent test. Moreover, there is evidence that subjects do not engage in labeling pictures of objects when they are presented in a rapid sequence. It is known that recall of items from a list of pictures is impaired when the picture labels have phonologically similar names (Schiano & Watkins, 1981). Coltheart (1999) examined this effect when pictures were presented in an RSVP sequence with exposure duration set at 1 s per item or 125 ms per item. The phonological similarity effect was found only with the longer exposure duration, indicating that subjects did not phonologically encode the object names when the more rapid presentation rate was used. Similarly, an early study conducted by Paivio and Csapo (1969) demonstrated that performance in a number of memory tasks for simple line drawings was impaired at an RSVP rate of 189 ms per item, presumably because there was insufficient time for implicit labeling. Thus, it is unlikely that subjects were actively encoding the names of the objects during presentation of lists of pictures with the rapid presentation rate used here.

Although we found cross-form priming in the picture-study group, there was no priming for the word-study group. Srinivas (1993) found only very small word-to-picture priming in a picture-fragment completion task, and small or absent priming effects seem to be a common result with this version of cross-form priming (Lachman & Lachman, 1980; Weldon & Roediger, 1987). We offer two possible reasons for the absence of priming of pictures by words in Experiment 3. First, the probability is low that an object name will elicit information about the object's visual form that closely matches the particular instantiation of the object that is presented at the time of test. Second, the relatively low accuracy for the word-study group in the visual-search task suggests that 75 ms may not have allowed sufficient time for conceptual processing of words.

Experiment 4

Experiment 4 was designed to address a rival explanation of the indirect memory test effects revealed in the experiments reported thus far. The study-phase search task we used was designed so that the conscious processing of each nontarget in a search would be confined to the brief moment during which the item was exposed. The stimuli appearing immediately before and after a particular item were expected to limit conscious processing to the window of time in which each item was visible. This assumption is part of the basis for our conclusion that information about an identified object can be encoded into long-term memory with only 75 ms of visual attention directed toward the object. It is possible, however, that subjects may have actively maintained information about some objects in working memory, even after the objects had disappeared from view. For example, in an RSVP list of 32 objects, a drawing of a camel might have been presented near the middle of the list. Having fleetingly identified that item, the subject potentially could continue to process information about it, such as retrieving its name or thinking about how the animal was posed, even while the next few objects or perhaps all of the remaining items on the list were presented. In the context of the search task, events of this nature might be considered a form of mind wandering (e.g., Giambra, 1995; Schooler, 2002). The few items that subjects might have maintained in working memory could have generated the priming effects we have thus far reported.

In Experiment 4, we addressed this possibility by giving subjects a surprise instruction at the end of a critical search list to report any items that they could remember seeing on the list. Items that might have been preserved in working memory should be reported under that instruction and could then be excluded from our assessment of priming on the subsequent masked identification task. With these items removed, any remaining priming could be ascribed more confidently to the benefits of encoding operations that included no more than about 75 ms of attentional processing. Critical items were presented on only the one search trial that was probed for report of items that might be in working memory. Once subjects had received that report instruction, they might have attempted on subsequent trials to retain items in working memory during list presentation. Therefore, the trials following the critical probed trial were treated as filler trials.

Method

Subjects. Twenty-six subjects were sampled from the same pool as in the earlier experiments.

Materials. Experiment 4 was a replication of Experiment 1 with the additional purpose of identifying items that might have been maintained in working memory during the presentation of the search list. This goal led to the following changes in method. The search task consisted of four instead of six trials with an exposure duration of 75 ms per item. Each of the four trials consisted of 40 items, with five filler items at the beginning of the list and five more at the end. Only 60 critical items were used, with 30 items randomly designated as nontarget items appearing on the third trial of the search task. That trial was designated as a target-absent trial to ensure that subjects attended to all items and did not cease attending to the display after detecting a target. The remaining 30 critical items were presented in the test phase. A set of 72 fillers was used to create the search lists for the three remaining trials of the search task. Eighteen of these filler items were randomly selected to be repeated, creating 90 tokens in total, which provided for 30 items on each filler trial. No filler item was repeated on the same trial. Finally, the masked object-identification test consisted of 60 critical items: 30 that had been presented as nontargets on the third search trial and 30 that had not been presented in the search task. The test began with a set of practice items as in the earlier experiments, then the 60 critical items were presented in a random order.

Procedure. Subjects performed the visual-search task as in Experiment 1. Two practice trials with relatively long exposure durations were presented, followed by four trials in which the exposure duration was 75 ms. Immediately following the response on the third trial, the following question appeared on the monitor, "In the list you just saw, you might have identified some of the pictures. If so, can you name them for the experimenter?" The probe question was intended to identify any items in the list that subjects might have identified and maintained in working memory. Subjects informed the experimenter of any items they could recall. Critical items that subjects reported at this stage were still presented in the test phase, but were excluded from the final analysis. The fourth search trial continued normally after the probe question. The masked object-identification test was identical to that in Experiment 1 except that it consisted of 60 critical trials.

Results and Discussion

Visual-search task. The mean proportion of correctly detected targets in the two filler trials in which the target was present was .87 (*SD* = .27). The mean false detection rate for the remaining two trials was .21 (*SD* = .35).

Masked object-identification test. Performance on the identification test replicated the priming effect found in Experiment 1, regardless of whether items reported during the search task were excluded. When items that subjects reported at the end of the critical search trial were included, the mean proportion of correct trials was .68 for items that had appeared as nontargets and .57 for nonstudied items. In the search task, subjects reported an average of 1.3% of the critical items at the end of the third search trial. Eliminating these items from the analysis of performance on the identification test had only a negligible impact--the mean proportion of studied items correctly identified was still .68. Performance on nonstudied items was, of course, not affected by this conditional treatment of the data. A repeated-measures ANOVA on the conditionalized data found that subjects were significantly more accurate at identifying previously seen items relative to nonstudied items, $F(1, 25) = 28.79$, $MSE = 0.177$. The 95% within-subject confidence interval for the proportion correct means was ±.032.

Experiment 4 was designed to address one possible explanation for the priming observed among objects that had been momentarily identified in a rapidly presented sequence. It is possible that for a small number of nontarget items, subjects may have retained information about them in working memory, even though doing so provided no advantage for the primary task. It could be these items, which would receive much more than just 75 ms of attentional processing, that were responsible for the priming effect. The results of Experiment 4 show, however, that when such items are excluded from consideration, a clear priming effect remains.

General Discussion

The most important finding of the present series of experiments is evidence for long-term memory encoding for non-target items that were presented for very brief durations. Subjects in Experiment 1 were presented pictures in an RSVP sequence at a duration of 75 ms per picture, unaware that their memory for these items would later be implicitly tested. In the second part of the experiment, they searched for target objects in RSVP lists and identified briefly presented individual pictures. In each test, half of the critical items had been presented in the study phase. Detection rate and identification accuracy were higher for items that had been presented earlier, suggesting that they had been encoded into memory and this encoding facilitated their later processing. This result is contrary to the claim that a process of memory consolidation must be applied to a stimulus that is attended for several hundred milliseconds before the item is stored in long-term memory (Potter, 1976; Subramaniam et al., 2000).

After establishing the existence of long-term memory representations following very brief exposures, we attempted to determine what information was included in these representations. We discovered in Experiment 2 that the memory episodes included a visual component, as evidenced by greater priming of an exact replication of the studied image relative to a mirror reversal of that image. Moreover, evidence for a conceptual component was suggested by cross-form priming in Experiment 3, in which a studied picture facilitated the identification of the name of the pictured object. The indirect memory test also showed evidence of memory encoding in Experiment 4 when items that may have been actively maintained in working memory during the RSVP stream were identified and eliminated from the analyses.

We propose that aspects of the design of the indirect test of memory used by Subramaniam et al. (2000) was the primary reason for the absence of a priming effect in their results. They used very few trials to measure baseline (nonstudied) target detection and embedded those trials among the first few that were presented to subjects. Low reliability in the measurement of baseline performance and possible changes in response criteria may have obscured possible priming effects in their study. In our experiments, we used equal numbers of trials for nonstudied and primed conditions and randomly distributed those trial types throughout the test phase. We also used a masked identification task that better conforms to principles of TAP, which may have further enhanced our ability to detect long-term memory effects of brief nontargets. .We argue that whether or not memory for an event is detected does not depend on uninterrupted processing of stimuli for a criterial length of time, but is instead determined by the relation between the procedures used to encode and to detect the memory.

Due to the exclusive use of indirect memory tests in the present studies, no claim can be made as to whether the long-term memory representations formed during the RSVP search lists would support performance on a direct test of memory. However, as mentioned above, previous studies using similar encoding situations obtained poor or at-chance performance on direct recognition memory tests (Intraub, 1981, 1984; Potter, 1976; Subramaniam et al., 2000; Whittlesea & Price, 2001). It may be claimed that the present results have demonstrated only that a memory consolidation process is not necessary to encode items into “implicit” memory, which is probed with indirect memory tests, leaving unresolved the issue of a consolidation process that encodes items into “explicit” memory, which has been extensively researched with recognition memory tests. Against this idea, Whittlesea and Price (2001) argued that the terms “implicit" and "explicit” have been a source of confusion as a result of being used to refer to separate memory stores as well as different ways of probing memory. Our use of the terms “indirect" and "direct” to describe a memory test is motivated by the view that information stored in memory can be used flexibly to support performance on different forms of memory tests depending on the goals and strategies of the subject. Thus, we have used memory tests different from the kind used in previous investigations of memory consolidation but this does not mean that we have investigated a memory system unrelated to processing operations that determine performance on direct tests. Rather, we suggest that the long-term priming effects we have demonstrated reveal characteristics of long-term memory information that might be recruited to support performance on a range of memory tests, depending on whether those tests induce processing operations similar to those that support identification of items on RSVP lists.

It could be that the priming effects we obtained were the result of repeating items three times each in the search task used in the study phase. Item repetition may have played a role in the mere exposure research mentioned earlier, as each geometric shape in the Kunst-Wilson and Zajonc (1980) study was presented five times, and Whittlesea and Price (2001) typically reported increased preference only for pictures presented more than once. The decision to repeat pictures in the encoding phases of the present experiments was motivated by the Whittlesea and Price findings. The results of Experiment 4, however, in which pictures were presented only once, provide evidence contrary to the argument that item repetition is necessary for long-term memory encoding.

We previously mentioned that Subramaniam et al. (2000) used the single-cell recording data of Tovee and Rolls (1995) to support their claim that a memory consolidation process requires several hundreds of milliseconds. The neurons recorded in the inferior temporal cortex of monkeys appeared to convey sufficient information to differentiate the experimental stimuli in the first 50 ms, yet these cells continued to fire for an additional 350 ms. Subramaniam et al. proposed that the additional 350 ms of firing reflects a memory consolidation process. The results from Tovee and Rolls and other single-cell recording research, however, also fit a different interpretation. Pictures presented in an RSVP sequence may initiate a chain of processing steps for each item--a chain that continues through the cognitive system even after the display of a particular stimulus has been replaced by a subsequent item. Neurons in the anterior superior temporal sulcus (STSa) do not start selectively responding until an average of about 100 ms after a stimulus has been presented (Keysers, Xiao, Földiák, & Perrett, 2001), and this was true even for pictures presented for as brief a duration as 14 ms in an RSVP sequence. The Keysers et al. results imply that seven subsequent pictures had been presented before neurons in the STSa began to selectively respond to the initial stimulus. Thus, processing of previous stimuli may be occurring at higher-level stages in the cognitive-perceptual system (e.g., inferior temporal cortex) while earlier stages (e.g., V1 cortex) are involved in processing current stimuli (Thorpe & Fabre-Thorpe, 2001; Tovee & Rolls, 1995). Each stage may consist of 20-50 ms of processing before it is conveyed to the next stage. In this way, an initial pass through the cognitive system will lead to a visual representation sufficient to differentiate among stimuli. As reported by Tovee and Rolls, the neurons will continue to fire after the initial 50 ms because not all of the information has been obtained in the first pass and additional information will contribute to a better visual representation, supporting performance on tasks that require more fine-grained visual information.

The idea that a brief stimulus initiates processing that continues beyond its visible duration, even when the stimulus is masked, has been raised in the context of the masked-priming paradigm (Forster, 2006). In masked priming, a mask is followed by a word (the prime), which is presented for a very brief duration and followed by a second word (the target) that also serves to mask the prime. Despite subjects being unaware of the prime, it still influences processing of the target (Forster & Davis, 1984). Research suggests, however, that processing of the prime is not completed within its duration of 50 ms before it is replaced by the target, but continues in parallel with the processing of the target (Forster, 2006). Indeed, evidence from ERP studies show that the N400 component typically occurs 400 ms after the onset of a stimulus even when that stimulus is presented for less than 100 ms in an RSVP sequence, suggesting that semantic analysis of the stimulus is occurring while subsequent stimuli are processed at earlier stages in the cognitive processing stream (Vogel et al., 1998; see also Hagoort & Brown, 2000; Sereno, Rayner, & Posner, 1998). Therefore, although pictures in the present studies were presented for only 75 ms before being masked by a subsequent item, it is likely that that exposure was sufficient to initiate visual and semantic processing that continued in parallel with the processing of subsequent items. The results of the present studies strongly suggest that this parallel processing will lead to memory encoding that later facilitates masked object identification of exact replications, mirror images, and alternate-format versions of the studied pictures.

Our evidence calls into question the claim that a process of memory consolidation carried out over several hundred milliseconds of uninterrupted stimulus processing is required for an item to be encoded into memory. It appears that the processing applied to very briefly presented items may continue for several hundred milliseconds even after they have been masked, but there is no indication that this processing is specifically directed at encoding the representation into memory. This processing instead involves later stages of the visual-cognitive system, and each stage is involved in creating a higher-level representation. We used indirect memory tests designed to be sensitive to information that may have been encoded at lower (e.g., visual) and higher (e.g., conceptual) levels of processing. The present studies suggest that the processing that occurs at each stage will leave a long-term impression on the cognitive system that may be detected when the testing conditions are appropriate.

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