INVESTIGATIONS OF THE COGNITIVE AND NEURAL PROCESSES SUPPORTING MEMORY FOR NEUTRAL AND EMOTIONAL WORDS

by

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Abstract

The cognitive and neural processes underlying memory formation may differ depending on the vividness, or detail, of information encoded. In **Chapter 1**, a divided attention paradigm was used to examine memory formation when resources are (a) devoted primarily to encoding and (b) directed away from encoding, and toward a secondary task. In condition (b) the memories formed often lacked vividness. The formation of these less detailed memories recruited right inferior prefrontal cortex (PFC) and left parahippocampal gyrus. The left inferior PFC and left anterior hippocampus were additionally recruited in condition (a) when vivid memories could be formed.

Investigations of memories' vividness have typically included only neutral information. The studies in **Chapter 2** revealed that emotional information is vividly remembered more frequently than information lacking emotional import. This enhancement occurred for words with valence only (i.e., negative words that did not elicit physiological arousal) as well as for arousing ("taboo") words, but was stronger for the arousing words.

In **Chapter 3** a divided attention paradigm was employed to investigate the contributions of automatic and controlled processing to the recollective enhancement for the emotional words. Automatic processes (unaffected by task manipulation) drove the enhancement for arousing words, whereas controlled processes (disrupted by task manipulation) supported the enhancement for words with valence only. Thus, dissociable cognitive processes contributed to the enhancement for the two types of emotional words.

In **Chapter 4**, fMRI was used to examine whether distinct encoding processes underlie enhanced memory for words with valence only versus words with arousal. Successful encoding of words with valence only was via a PFC-hippocampal network associated with controlled encoding processes (e.g., elaboration and rehearsal), whereas successful encoding of arousing words was mediated by an amygdalar-hippocampal network that may be important for automatic processing of emotional content.

In conclusion, distinct neural processes appear to support the ability to form vivid memories as compared to less detailed ones. The specific cognitive and neural processes depended on the emotional nature of the stimuli. Vividly-remembered neutral words, and words with valence only, relied on similar encoding processes. In contrast, dissociable processes mediated successful encoding of vividly-remembered arousing words.

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Publications

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Table of Contents

Preface

This dissertation comprises an introduction, four chapters, and a conclusion. The introduction frames the overarching question addressed in the chapters: What are the cognitive and neural processes that support memory formation for neutral and emotional words, and how does divided attention alter those processes? Each chapter then addresses a component of this question: Chapter 1 probes the effects of divided attention on the cognitive and neural processes contributing to memory for neutral words; Chapter 2 examines whether individuals' memories for emotional information are more vivid or detailed than their memories for neutral information; Chapter 3 investigates the effect of divided attention on memory for emotional and neutral words; and Chapter 4 addresses the neural processes supporting encoding of emotional versus neutral words. Each chapter is intended to stand on its own, and the relevant references, tables, and figures are presented at the end of each chapter, for ease of access. The conclusion summarizes the major findings presented in the chapters, and discusses future directions for research.

Introduction

In traditional studies of memory, stimuli are specifically chosen such that they elicit no emotional responses. This active avoidance of affect, however, has left a void in our understanding of memory processes: The information we encounter in daily life is often infused with emotional salience, yet it remains unclear how emotional content influences the cognitive and neural processes used to learn, or to retrieve, information. Toward bridging this gap, the studies reported here integrate two prevalent research findings: the detrimental effects of divided attention on memory, and the memory enhancement for emotional as compared to neutral stimuli.

Dual-Process Theory: Recognition as Recollection and Familiarity

Our memories can include varying amounts of detail. Sometimes when driving down a street, we can feel that our surroundings are familiar: We sense that we have seen a particular restaurant before, or that we have driven down the stretch of road on a prior occasion. Yet, we cannot retrieve any specific details about the past events that have led to that feeling of familiarity. Perhaps after some time, we will remember that, in fact, we were in that restaurant many years ago for a wedding reception, and the details of that event will come flooding back into our minds.

According to the dual process theory, these two types of recognition memory result from dissociable processes: recollection and familiarity (Jacoby, 1991; Mandler, 1980). Recollection includes the re-experiencing of information processed at encoding (recapitulation), whereas familiarity lacks this detail about the encoding episode, and instead is a feeling of increased item strength resulting from the recent presentation of an item. Thus, passing the restaurant and sensing that you have been there previously is an example of a feeling of *familiarity*, whereas *recollection* occurs when the details, or context, surrounding the visit to the restaurant (e.g., the wedding reception) have been retrieved. Recollection is thought to be a slower, attention-demanding process, whereas assessments of familiarity are faster and more automatic. As in the above example, we often have a sense of prior encounter with a stimulus, and only later are capable of retrieving the details of that prior encounter. Laboratory studies, by varying the amount of time given to retrieve information, have confirmed that assessments of familiarity can occur more rapidly than retrieval of detailed, recollective information (Hintzman & Caulton, 1997; Gronlund, Edwards, & Ohrt, 1997; Hintzman & Curran, 1994; Jacoby, 1999; see Yonelinas, 2002, for review).

Detrimental Effects of Divided Attention on Memory

The dissociation between recollection and familiarity may explain the effect that divided attention has on memory: When our attention is divided as we learn information, our memory suffers (Craik et al., 1996; Baddeley et al., 1994; see Yonelinas, 2002, for review). This finding has been replicated in a plethora of behavioral studies aimed at understanding the cognitive processes affected by attention allocation. In the most widely used paradigm, participants are asked to learn words, or to retrieve studied words, while concurrently performing a secondary task, such as motor tracking or auditory discrimination. By varying the difficulty of the secondary task, the resources devoted toward the encoding task are modulated. Nevertheless, individuals are capable of learning information, even when resources are shifted toward a secondary task. The hypothesis addressed in **Chapter 1** is that neural processes related to recollection may be more likely to support memory formed with relatively full attention devoted toward learning, whereas neural processes tied to familiarity may be more likely to support memory formed when resources are diverted toward a difficult second task.

Memory for Emotional Information

An abundance of research has been devoted toward understanding the cognitive and neural processes contributing to memory for neutral information. In comparison, very little research has been aimed at investigating the cognitive and neural processes supporting memory for emotional information. The goals of Chapters 2, 3, and 4 are to elucidate the cognitive and neural processes that contribute to emotional memory, and the extent to which they overlap with processes important for memory for neutral information.

Memory Enhancement for Emotional Information

Observations in everyday life provide abundant evidence that facts and events associated with strong emotion are better remembered than those that are not. The extreme example of this phenomenon is flashbulb memory, in which an individual retains a long lasting, and vividly detailed, memory of an emotional event (Davidson & Glisky, 2002; Tekcan, 2001; Schmolck, Buffalo & Squire, 2000; Finkenauer et al., 1998; Conway et al., 1994). For example, nearly everyone who was over the age of approximately 6 (Winograd & Killinger, 1983) claims to remember their whereabouts at the moment they learned that JFK had been assassinated. Laboratory studies have confirmed that, even when the events are not as personally relevant or surprising, individuals are nevertheless more likely to remember emotional information than neutral information (Heuer & Reisberg, 1990; Cahill & McGaugh, 1995; Kensinger et al., 2002). Thus, if a person is shown 100 pictures, 50 of which are neutral (e.g., fish, books) and 50 of which are emotional (e.g., snakes, injured people), he or she will remember more of the emotional pictures than the neutral pictures. This quantitative benefit for emotional information has been demonstrated using a variety of stimuli, including short stories (Heuer & Reisberg, 1990; Kensinger et al., unpublished data); words (Phelps, LaBar, & Spencer, 1997; Kensinger et al., 2002; Tabert et al., 2001; LaBar & Phelps, 1998), sentences (Kensinger et al., 2002), film slides (Cahill & McGaugh, 1995; Adolphs et al., 1997) and pictures (Kensinger et al., 2002; Bradley et al., 1992).

Effects of Valence and Arousal

Emotional information may differ from neutral information along two orthogonal dimensions: Valence (how positive or negative an item is) and arousal (how calming/soothing or exciting/agitating an item is; Lang, Greenwald, Bradley, & Hamm, 1993; Russell, 1980; Russell & Bullock, 1985; Russell, Lewicka, & Niit, 1989). The majority of investigations of the effects of emotion on memory have used stimuli with both valence and arousal (e.g., negative, arousing stimuli), and have focused on the relation between arousal and memory enhancement (Bradley, Greenwalk, Petry, & Lang, 1992; Hamann, Cahill, & Squire, 1997). Emotional arousal clearly is a critical factor contributing to the emotional enhancement effect for many items (e.g., Cahill, Prins, Weber &

McGaugh, 1994; Cahill & McGaugh, 1995). Nevertheless, there is evidence that memory can be enhanced even when stimuli have valence only, and do not elicit arousal (e.g., Ochsner, 2000; Kensinger et al., 2002). The cognitive and neural processes supporting this enhancement, and the extent to which they overlap with those important for enhancement for arousing information, remain underspecified. The studies reported in **Chapters 2, 3, and 4** all use some items that have only valence (i.e., negative words that do not elicit a physiological response) and others that elicit arousal ("taboo" words). This manipulation allows the cognitive (**Chapter 2 and 3**) and neural (**Chapter 4**) processes that contribute to the memory enhancement effect to be addressed separately for items with only valence as compared to items that evoke arousal.

Cognitive Processes Supporting Emotional Memory Enhancement: Recollection Enhancement?

Although the quantitative benefit for emotional information has been well-documented, the cognitive and neural processes underlying the memory benefit remain underspecified. One intriguing question is whether there is a qualitative as well as a quantitative difference in memories for emotional information. A rephrasing of this question is whether "recollection," the retrieval of a vividly detailed memory, is more likely to occur for emotional information. The data from flashbulb memories suggests that this may be the case: Individuals' memories for highly emotional events tend to include more detail (e.g., location, clothing worn, weather outside, time of day, etc.) than do memories associated with less emotional events (Davidson & Glisky, 2002; Schmolck, Buffalo, & Squire, 2000; Heuer & Reisberg, 1990). One study (Ochsner, 2000) provides evidence that this type of qualitative difference results for negative as compared to neutral pictures. **Chapter 2** investigates whether memories of negative information include more detail and contextual information than memories of neutral information, and whether the effect occurs for verbal as well as visual information.

Cognitive Processes Supporting Emotional Memory Enhancement: Automatic or Attention-Demanding Encoding Processes?

Another question is whether automatic or attention-demanding processes at encoding contribute to the memory benefit for emotional information. Encoding could be affected by automatic processes, such as automatic orienting toward emotional stimuli (Bargh, Chaiken, Govender, & Pratto, 1992; Fama et al., 2001; Pratto & John, 1991; Reimann & McNally, 1995; Williams, Mathews, & MacLeod, 1996) or emotion's modulation of perceptual processes (Anderson & Phelps, 2001; Dolan, 2000; Tabert et al., 2001). Multiple lines of evidence suggest that emotional stimuli can be processed automatically: At least in some circumstances, individuals appear able to process fear-related visual stimuli in the absence of attention (Stenberg, Wilking & Dhal, 1998) or conscious awareness (Ohman, 2002). Prioritized processing is suggested in studies in patients with unilateral neglect: These patients are more likely to recognize an emotional stimulus presented in the contralesional field than a neutral stimulus (Vuilleumier & Schwartz, 2001). Neurally, emotional stimuli have been found to activate the amygdala even when individuals are unaware that the information has been presented (Morris et al., 1998, Whalen et al., 1998; Vuilleumier et al., 2002; but see Pessoa, Kastner, & Ungerleider, 2002); thus, some of these automatic effects may occur because emotion activates the amygdala, which in turn modulates the processing of lower-level, pre-attentive, perceptual areas (LeDoux, 1995; Tabert et al., 2001).

Intentional processes may also be important for the memory enhancement effect. Individuals may be more likely to elaborate on emotional information (Christianson & Engelberg, 1999): Emotional material may have more personal relevance, and may thus be more likely to be associated with autobiographical information (Doerksen & Shimamura, 2001). Emotion also may serve as a categorical cue and thus it may be easier to semantically cluster emotional information (Phelps, LaBar, & Spencer, 1997). The studies reported in **Chapter 3** use a divided attention paradigm to address the relative contributions of automatic and attention-demanding processes to the enhancement effect for emotional information.

Neural Processes Supporting Emotional Memory Enhancement

Lesion studies have provided abundant evidence that the amygdala is critical for the emotional memory enhancement effect. Patients with damage to the amygdala do not show the enhancement effect for emotional information (Kensinger et al., 2002; Adolphs et al., 1997; Phelps et al., 1997; Cahill et al., 1995; Buchanan et al., 2001). In contrast, amnesic patients with spared amygdala, but partial damage to other medial temporal lobe structures, do show the enhancement effect (Hamann et al., 1997a, 1997b). Thus, the declarative memory enhancement effect appears to be particularly reliant on the amygdala. Recently, neuroimaging studies have confirmed a role of the amygdala in memory for emotional information: Amygdalar activation during encoding is predictive of subsequent memory for emotional, but not neutral, information (Cahill et al., 1996; Canli et al., 2000; Hamann et al., 1999; Tabert et al., 2001).

These studies leave a number of questions unanswered. First, many of these studies did not use whole-brain imaging, but rather focused on a-priori regions of interest (e.g., the amygdala). Thus, the neural networks contributing to the emotional memory enhancement effect remain underspecified. Second, in the prior studies, stimuli always contained both valence and arousal (i.e., were negative and arousing, or positive and arousing). Thus, the relative contributions of these two dimensions has not been specified. **Chapter 4** reports an fMRI investigation using whole-brain imaging to explore the neural processes supporting the enhanced memory for words with valence only, and words with arousal, as compared to neutral words. This methodology allowed for the investigation of the neural processes that lead to the formation of vivid memory for neutral information, and the neural underpinnings of the recollective enhancement for emotional information.

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Chapter 1

What Neural Correlates Underlie Successful Encoding and Retrieval? An fMRI Study Using a Divided Attention Paradigm

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Abstract

If attention is divided during learning, memory suffers. Nevertheless, individuals can learn information with divided attention. This event-related fMRI study (N=17) investigated what neural processes support (a) learning with divided attention, and (b) retrieval of information learned with divided attention. Participants encoded words (Is the word abstract or concrete?) while performing an auditory discrimination task (press a button whenever an auditory pattern changes). The auditory task was easy or hard, depending on the similarity of the patterns. A behavioral study indicated that detailed ("recollective") information was more likely to be present for words encoded with the easy versus the hard concurrent task. Words encoded with the hard versus the easy concurrent task, in contrast, were more likely to rely on less detailed ("familiarity"-based) information. Functional MRI revealed encoding-related activation in left prefrontal cortex (PFC) and left hippocampus that was linked to successful memory formation only for items encoded with the easy task. In contrast, activation in right PFC and left parahippocampal gyrus was linked to successful memory for all items. Thus, successful encoding with the hard concurrent task was supported by a subset of the regions recruited for successful encoding with the easy task. The neural processes recruited for successful retrieval also depended on the encoding condition: Left PFC was disproportionately recruited for retrieval of items encoded with the easy task, whereas right PFC was disproportionately recruited for retrieval of items encoded with the hard task. These findings may reflect left-sided specialization for "recollective" memories and right-sided specialization for "familiarity-based" traces.

The term "divided attention" refers to an experimental paradigm in which participants learn information while performing a concurrent task that is easy (taking few resources from the encoding operation) or hard (shifting resources from the encoding operation[1]). Participants' memory is worse for items encoded with a hard than with an easy secondary task (Baddeley et al., 1984; Craik et al., 1996; Naveh-Benjamin et al., 2000a, 2000b). PET studies using a divided attention paradigm found less activation in regions of prefrontal cortex (PFC) with performance of a hard secondary task versus an easy one (Fletcher et al., 1995; Shallice et al., 1994; Fletcher et al., 1998; Anderson et al., 2000; Iidaka et al., 2000). The PFC regions in which activation was affected are those that have been linked to episodic encoding (Paller & Wagner, 2002; Fletcher et al., 1998; Kirchhoff et al., 2000; Wagner et al., 1998). These regions may have shown greater activation during encoding with the easy versus the hard task because some encoding-related processes were not carried out with concurrent performance of a hard secondary task (Fletcher et al., 1995; Shallice et al., 1994; Iidaka et al., 2000).

Despite evidence that encoding processes are disrupted by divided attention, individuals can successfully encode some information while performing a hard secondary task. This finding raises the question: What neural substrates support successful memory formation when resources for encoding are reduced (i.e., during concurrent performance of a hard task)?[2]. One possibility is that the same regions that are usually implicated in successful

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[1] We remain neutral as to whether the divided attention manipulation at encoding taxes a general attention system or a working memory system (or these two systems may be equivalent).

memory formation (Wagner et al., 1999; Kirchhoff et al., 2000; Otten & Rugg, 2001; Brewer et al., 1998; Fernandez & Tendolkar, 2001; Fernandez et al., 1999; Paller & Wagner, 2002) continue to support successful encoding during performance of a hard concurrent task. An alternate option is that only a subset of the regions that typically support successful encoding continue to do so during performance of a hard task.

To understand why this second option could occur, consider that individuals can form two kinds of memories: (a) vivid, detailed memories that they can "remember" or "recollect," or (b) memories that lack detail and provide only a feeling that the item was presented (sense of "knowing" or "familiarity"; Mandler, 1980; Jacoby, 1991; Gardiner & Java, 1993; Tulving, 1985; Yonelinas, 2002). Formation of vivid, "recollective" memories is thought to require more attention than formation of less detailed traces; thus, divided attention may disproportionately affect the encoding of detailed memories (Yonelinas, 2001; Yonelinas, 2002)[3]. Activation in the subset of brain regions that allows less detailed memory formation may relate to successful encoding even with divided attention, whereas activation in regions that support detailed memory formation may not.

If divided attention qualitatively alters the memories formed, the divided attention manipulation could affect not only the neural processes recruited for successful memory formation, but also those recruited for successful retrieval. Retrieval of detailed, "recollective" memories may rely more on left PFC

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[2] The requisite blocked design of PET prevented investigation of this issue. The event-related fMRI design of this study allows correlation of single events during encoding with later retrieval, thus providing a way to address this question.

(Henson et al, 1999a, 1999b; Nolde et al., 1998a, 1998b; Johnson et al., 1997; Rugg et al., 1999) and the hippocampus (Eldridge et al., 2000; Davachi et al., 2001), while retrieval of "familiarity"-based memories may rely on right PFC (Eldridge et al., 2000; Henson et al., 1999) and the parahippocampal gyrus (Davachi et al., unpublished data; Strange et al., 2002). We, therefore, hypothesized that the left PFC and left hippocampus would be disproportionately recruited for retrieval of words encoded with the easy concurrent task, whereas the right PFC and left parahippocampal gyrus would be disproportionately recruited during retrieval of words encoded with the hard concurrent task.

BEHAVIORAL COMPANION STUDY

To confirm that the difficulty of the secondary task at encoding affected the amount of detail that could be retrieved, we conducted a behavioral study outside of the scanning environment.

Methods

Participants

Participants in this experiment comprised 24 young adults (12 women). They were matched to participants in the imaging study in age (ages 20-35 years, mean = 26.4) and education level (14-18 years, mean = 16.3).

Materials and Methods

Encoding

The stimuli were 480 words, with written frequencies ranging from 10 to 100 (Kuchera and Francis, 1967). They were presented one at a time in Geneva

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[3] Fletcher, Shallice and colleagues (Fletcher et al., 1995; Shallice et al., 1994) have proposed that divided attention may disrupt the ability to for explicit memories, while allowing formation of implicit memories.

48-point font, using MacStim (David Darby, WhiteAnt Occasional Publishing, West Melbourne, VIC, Australia). Stimulus words were divided into four encoding runs, each with 120 words.

Participants completed two encoding tasks, each followed by a retrieval task. In the encoding task, participants saw words for 2 sec each, and rated each word as abstract or concrete by pressing a button with their right middle or ring finger, respectively. Because we wanted the behavioral encoding task to be identical to that performed in the scanner, fixation crosses were interspersed pseudorandomly between the words. Participants made no response when fixation occurred.

In addition to making the abstract-concrete decisions, participants simultaneously performed an auditory discrimination task. For this task, 1.5 sec auditory patterns (created using Sound Edit – MacroMedia, Inc, San Francisco, CA), were presented continuously as people rated words and also when they viewed the fixation crosses. The participants' task was to listen to these patterns and to press a button with their left index finger every time a sound pattern changed from pattern A to pattern B (or from B to A). The difficulty of the auditory discrimination task was related to the similarity of auditory patterns A and B. In the easy version of the task, the two auditory patterns were rhythmically distinct and thus easy to discriminate. In the hard version, the patterns were rhythmically similar and hard to discriminate. Participants were given an instructional cue as to whether the secondary task would be "Easy" or "Hard," and that task version continued for 30 sec, until the next instructional cue (Figure 1).

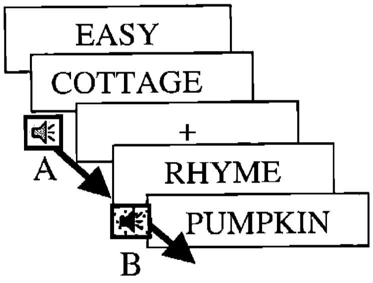

Figure 1. The instruction frame and first 8 sec of a representative encoding pseudoblock. A 2-sec instruction frame indicated the encoding task (classify words as abstract or concrete) and difficulty of the auditory discrimination task (easy or hard). Words were presented for 2 sec each and were pseudorandomly intermixed with fixation crosses. Sound patterns played throughout the pseudoblock, and participants pressed a button when they noted the sound pattern changed (e.g., from "pattern A" to "pattern B").

Retrieval

Following each of the encoding tasks, participants performed a recognition task with 72 previously presented words and 48 nonpresented words. Pilot data suggested that with this breakdown, participants responded that approximately half of the stimuli were presented previously. Participants were asked to indicate via button press whether they (a) "remembered" the word from the encoding list, (b) "knew" the word was presented previously, or (c) thought the word was "new" (nonpresented). A "Remember" response indicated that participants had a vivid memory of the presented item, whereas a "Know" response indicated that participants lacked a specific memory of the item's presentation, but sensed that it had been presented recently (Jacoby, 1991; Tulving, 1985).

Data Analysis

Data were analyzed in two ways. First, we calculated the corrected recognition scores (% "remember" hits - % "remember" false alarms or % "know" hits - % "know" false alarms). Second, we computed recollection and familiarity scores as suggested by Yonelinas et al. (1998). These scores take into account the fact that the probability of making a "know" response to a presented word is constrained by the number of "remember" responses made to presented words because participants were instructed to respond "know" to items that are familiar and not recollected. Analyses consisted of repeated-measures ANOVA with secondary task type (easy, hard) and memory strength (Remember, Know; Recollection, Familiarity) as within-subject factors, and subsequent t tests. All reported p values are two-tailed.

Results

Table 1 shows "Remember" scores, and "Know" scores in each of the conditions. All scores were corrected for false alarm rate (% hits - % false alarms). Repeated measures ANOVA, calculated either on the raw "Remember" and "Know" scores, or on the computed "Recollection" and "Familiarity" scores (Yonelinas et al., 1998) indicated a significant effect of encoding difficulty (F(1,23)=6.4, p<.01), and an interaction between memory strength (Remember versus Know or Recollection versus Familiarity) and encoding difficulty (F(1,23)=6.4, p<.01).

Table 1. Corrected recognition performance as a function of encoding condition in the behavioral companion study (Mean, SD).

	Remember	**Know**
Encoding with Easy Distractor	43 (18)	14 (28)
Encoding with Hard Distractor	28 (12)	24 (21)

The results of this behavioral companion study confirmed that the hard auditory task at encoding altered the type of memory trace formed. Items encoded with the hard auditory task were recognized by only a sense of prior encounter ("Know" response) more frequently than items encoded with the easy auditory task. Items encoded with the easy auditory task, in contrast, were recognized based on detailed information about the item's presentation ("Remember" response) more frequently than were items encoded with the hard auditory task.

FUNCTIONAL MRI STUDY

Having confirmed in the behavioral study that the manipulation of secondary task difficulty affected overall memory, as well as the richness of the memory traces formed, we then examined what effect this manipulation of secondary task difficulty would have on the neural processes underlying successful encoding and retrieval.

Methods

Participants

The participants comprised 22 right-handed, native English speakers. Five participants were excluded due to scanner malfunction (1 man, 1 woman), sound presentation failure (1 man), or excessive head movement (1 man, 1 woman). The remaining 17 participants (9 men, 8 women) were ages 20-35 (mean age = 26.1) with 14-18 years of education (mean = 16.0 years). Participants were screened to exclude those with any history of neurological or psychiatric disorder, and no participants were taking centrally acting medications.

Materials and Methods

General Methods

Before entering the scanner, participants performed a practice encoding and retrieval run. Once in the scanner, they completed an additional short practice run to allow familiarization with the presentation of the sound patterns via headphones. Participants were scanned during three encoding and three retrieval runs.

Encoding

The encoding task was identical to that described in the behavioral study. Each encoding run included 12 30-sec pseudo-blocks; each pseudo-block consisted of 10 words, each presented for 2 sec. The times of the word onsets were jittered with fixation crosses to allow for optimal accuracy and efficiency of estimation of the hemodynamic response to each stimulus (Dale et al., 1999). We used the optseq program (part of the FS-FAST analysis tools; http://surfer.nmr.mgh.harvard.edu/optseq, written by D. Greve, Athinoula A. Martinos Center, Charlestown, MA), which determines stimulus optimization (i.e., the optimal word onsets) given the repetition time (TR), number of event types, time per event type, and number of acquisitions. A description of the calculations employed in the development and implementation of this stimulus optimization program can be found in (Burock et al., 1998; Dale, 1999).

Although task type was blocked (i.e., participants performed either the hard distractor task or the easy distractor task for 30-sec periods), we could still resolve the hemodynamic response associated with each individual item because the items were jittered with fixation (Dale, 1999; Burock et al., 1998). The analysis of the data was, therefore, event-related.

Retrieval

A recognition run followed each encoding run. Each recognition run included 120 words, with 60 fixation points pseudorandomly intermixed to provide jitter. Across the recognition runs, 108 words had been encoded in the easy discrimination condition (half retrieved in the hard condition; half retrieved in the easy condition); 108 had been encoded in the hard discrimination condition (half retrieved in the hard condition; half retrieved in the easy condition); and 144 new words were pseudorandomly intermixed (half in the easy condition). The order of the encoding-recognition runs was counterbalanced across the participants.

Control Experiment

In a control experiment, 9 young adults (6 males, ages 18-30), performed only the auditory discrimination task (without the encoding or retrieval tasks). As in the main experiment, an instructional cue informed the participants whether the task would be "Easy" or "Hard," and the tasks were presented in 30 sec blocks. In addition, there was a "No task" condition, which served as the baseline. Throughout all task conditions, participants viewed a fixation cross on the screen, in addition to monitoring the sound patterns. The critical comparison was between the hard task and the easy task conditions.

Scanning Protocols

Imaging was performed on a Siemens (Erlangen, Germany) Allegra 3 Tesla head-only MRI scanner with a 36-cm inner diameter asymmetric gradient coil. Head motion was minimized using pillows and foam padding around the head. For each participant, 2 magnetization prepared rapid gradient echo (MP-RAGE) structural scans optimized for gray/white contrast were collected to provide detailed anatomical information. Following the structural scans, a series of echoplanar functional scans was collected to provide images sensitive to blood oxygen level-dependent (BOLD) contrast. Functional T2*-weighted images were acquired using a single-shot echoplanar sequence (tau=-25 ms, TE=30 ms, TR=2000 ms, 3.13 mm in-plane resolution, 5 mm slice thickness, no skip). Slices were aligned along the anterior commisure – posterior commisure line. Each scan lasted 6 min 24 sec, during which 92 images were acquired in an interleaved fashion for each of 22 axial slices.

Data Analysis

Data were motion corrected using the Analysis of Functional NeuroImages (AFNI) motion correction algorithm (Cox & Jesmanowicz, 1999). We excluded participants whose motion exceeded two functional voxels. We conducted analyses both with and without global signal intensity normalization. The results did not differ qualitatively; we therefore report the normalized data here.

We used selective averaging and deconvolution of the BOLD signal. The BOLD signal was modeled as a linear combination of hemodynamic responses, offset, and trend embedded in Gaussian nose (Boynton et al., 1996; Dale & Buckner, 1997; Dale, 1999). The hemodynamic response to a particular stimulus type was modeled as a sum of delta functions over a fixed time window phase-locked to the presentation of the stimulus. No response shape for this function was assumed, but it was assumed that the response to a particular stimulus type was the same for every presentation of that stimulus type, and that the overlap of temporally adjacent responses was linear. This signal model was inverted to obtain the average hemodynamic response to each stimulus as if that stimulus were presented in isolation, allowing for the resolution of individual events (Boynton et al., 1996; Dale et al., 1997; Dale, 1999).

Effects for each condition were estimated using a participant-specific, fixed-effects model. The participant-specific effects from each of these contrasts were entered into a second-level group analysis treating participants as a random effect. Regions were considered reliable if they consisted of at least 5 contiguous voxels that exceeded a threshold of $p < .001$ (uncorrected).

Regions of interest (ROI) were defined functionally based on the contrasts of all encoding versus baseline, or all retrieval versus baseline. The defined ROIs were, therefore, unbiased with respect to the contrast of interest (easy versus hard concurrent task; remembered versus forgotten). ROI analyses examined whether there was a reliable Condition (e.g., words remembered, words forgotten) by Time (0-14 sec) interaction. Time represented the timecourse of the signal change; thus, an interaction between Condition and Time indicated that the signal change differed based on Condition during a specific part of the timecourse (i.e., the interaction indicated that the Condition effect was not related to a nonspecific elevated signal change). Planned contrasts further examined whether the peak percentage signal change (across timepoints 2s – 10s, as compared to the Fixation-Sound baseline) differed for two conditions (e.g., remembered, forgotten or easy, hard).

We resampled the functional data into standardized space (Spherical, Talairach) to allow averaging of group data. Automatic spherical resampling (Fischl et al., 1999, 2001; Dale et al., 1999) examined the effect of condition on cortical activation for the group. Automatic Talairach resampling using the MNI atlas (Mazziotta et al., 1995) examined the effect of condition (e.g., hard versus easy encoding) on subcortical activation for the group of participants. All group data were analyzed using random-effects analyses (Friston et al., 1999).

Results

Behavioral Performance

Accuracy. The presence of the hard secondary task at encoding led to poorer memory than did the presence of the easy secondary task (t=5.1, p<.01). In contrast, the difficulty of the secondary task at retrieval did not affect memory performance (p>.1). Repeated-measures ANOVA indicated no effect of memory process (encoding, retrieval) [F(1,16)=.10, p>.3], a significant effect of task difficulty [F(1,16)=4.42, p<.01] on memory performance, and a significant task difficulty by memory process interaction [F(1,16)=5.25, p<.01], indicating that the difficulty manipulation had a greater effect at encoding than at retrieval (Table 2). These results are consistent with the findings of numerous behavioral studies (Craik et al., 1996; Craik et al., 2000; Naveh-Benjamin & Guez, 2000; Naveh-Benjamin et al., 1998), and are consistent with the performance we found on this task in a behavioral pilot study.

Table 2. Mean corrected (% hits - % false alarms) recognition performance (SD) as a function of secondary task difficulty and memory process.

		RETRIEVAL	
		Easy Distractor	**Hard Distractor**
ENCODING	**Easy Distractor**	64 (21)	62 (21)
	Hard Distractor	56 (16)	57 (22)

Reaction Times for Noting Sound Pattern Changes. A comparison of reaction times for the two auditory discrimination conditions indicated that participants were slower to respond to auditory pattern changes when the discrimination was hard than when it was easy (Table 3) [F(1,16)=733.32, p<.0001]. Participants were slower at indicating the sound pattern change (regardless of auditory task difficulty) when it occurred at retrieval than at encoding [F(1,16)=6.64, p<.01], but there was no interaction between task difficulty and memory process [F(1,16)=.91, p>.2], indicating that the increased time to respond to the hard versus the easy auditory pattern changes was similar at encoding and retrieval. These results are also consistent with those of prior behavioral studies, as well as the performance of participants on this task when assessed outside of the scanner.

Table 3. Reaction times (ms) to the change in sound patterns as a function of secondary task difficulty and memory process (Mean, SD).

Encoding with Easy Distractor	Encoding with Hard Distractor	Retrieval with Easy Distractor	Retrieval with Hard Distractor
510 (220)	930 (210)	600 (170)	980 (180)

Reaction Times for Rating Words as Abstract/Concrete or Old/New. Participants' reaction times for rating the words as abstract or concrete were not affected by the difficulty of the auditory discrimination task at encoding; nor were the reaction times for making old or new decisions at retrieval affected by secondary task difficulty (Table 4): Repeated measures ANOVA revealed no effect of task difficulty at encoding or at retrieval, and no interaction between encoding difficulty and retrieval difficulty.

Table 4. Reaction times (ms) to retrieve words as a function of secondary task difficulty at encoding and retrieval (Mean, SD).

		RETRIEVAL	
		Easy Distractor	**Hard Distractor**
ENCODING	**Easy Distractor**	830 (230)	890 (220)
	Hard Distractor	850 (200)	870 (290)

Table 5. Brain regions showing significantly more activation during encoding with the easy task than during baseline. Regions were defined as significant if they included at least 5 functional voxels at an uncorrected significance of p<.001.

Brain Region	**Hemisphere**	**Talairach Coordinates (x, y, z)**	**Brodmann Area**
Superior frontal gyrus	L	-4, 6, 55	6
Middle frontal gyrus	L	-55, 36, 16	45/46
Middle frontal gyrus	L	-43, 28, 28	9/46
Inferior frontal gyrus	L	-32, 24, 10	45
Inferior frontal gyrus	L	-48, 38, -12	46
Precentral gyrus	L	-28, -25, 38	4
Postcentral gyrus	L	-48, -17, 49	1
Superior parietal lobule	L	-28, -60, 51	7
Inferior parietal lobule	L	-51, -22, 19	40
Inferior temporal gyrus	R	40, -70, -10	37
Occipital gyrus	L	-20, -93, -2	18
Thalamus	L		

fMRI Results: Encoding

We first conducted voxel-based statistical analyses, which revealed the voxels of the brain that showed condition-related activity above a threshold of $p<.001$. These analyses revealed that encoding with either the easy or the hard distractor task (as compared to baseline) elicited activation in occipital, parietal, and frontal regions bilaterally, and in the left medial temporal lobe (MTL). Interestingly, the regions recruited were similar regardless of the difficulty of the secondary task: In a direct contrast of encoding with the hard distractor task versus encoding with the easy distractor task, we found no evidence of additional neural circuits that were recruited to coordinate performance of the encoding task with performance of the more difficult auditory task. Even with the threshold dropped to $p<.05$, the same occipital, parietal, and frontal regions were recruited in both tasks (Tables 5 and 6).

Table 6. Brain regions showing significantly more activation during encoding with the hard task than during baseline. Regions were defined as significant if they included at least 5 functional voxels at an uncorrected significance of $p<.001$.

Brain Region	Hemisphere	Talairach Coordinates (x, y, z)	Brodmann Area
Superior frontal gyrus	L	-4, 3, 59	6
Middle frontal gyrus	L	-51, 36, 16	46
Cingulate gyrus	R	4, 36, 20	32
Precentral gyrus	L	-47, -17, 49	4
Postcentral gyrus	L	-60, -18, 20	1
Superior parietal lobule	R	43, 18, 54	7
Inferior parietal lobule	L	-35, -36, 46	7
Inferior temporal gyrus	L	-35, -47, -18	37
Occipital gyrus	L	-8, -93, 1	18
Thalamus	R		

These results contrast with the view that increasing task coordination demands requires bringing on-line additional neural resources (e.g., D'Esposito et al., 1995) and instead suggest that the demands required for a more difficult task coordination can be met by the same regions active during a less demanding task coordination condition (see also Adcock et al., 2000; Bunge et al., 2001).

Table 7. Brain regions showing significantly more activation during encoding with the <u>easy task</u> than during encoding with the <u>hard task</u>.

Brain Region	**Hemisphere**	**Talairach Coordinates (x, y, z)**	**Brodmann Area**
Superior frontal gyrus	L	-4, 14, 51	8
Middle frontal gyrus	L	-40, 54, -16	10
Inferior frontal gyrus	L	-47, 9, 18	44
Precuneus		0, -67, 62	7
Superior temporal gyrus	L	-60, -34, 9	22
Inferior temporal gyrus	L	59, -13, -23	20

We then conducted ROI analyses that further examined activation related to task difficulty (within regions active during encoding with both tasks). These analyses indicated that the magnitude of responses (maximum signal change) in the left inferior and left superior frontal regions were greater during encoding with the easy as compared to with the hard auditory task (Table 7; Figure 2).

These results indicate that regions associated with encoding, including a region of left ventrolateral PFC (BA 44; Talairach coordinate: -48, 19, 25), showed less activation during concurrent performance of the hard task than during concurrent performance of the easy task. These data are in general agreement with the results of prior PET studies of divided attention (Fletcher et al., 1995;

Fletcher et al., 1998; Shallice et al., 1995; Iidaka et al., 2000; Anderson et al., 2001), and suggest that some encoding processes were not being carried out effectively during encoding with the hard auditory task.

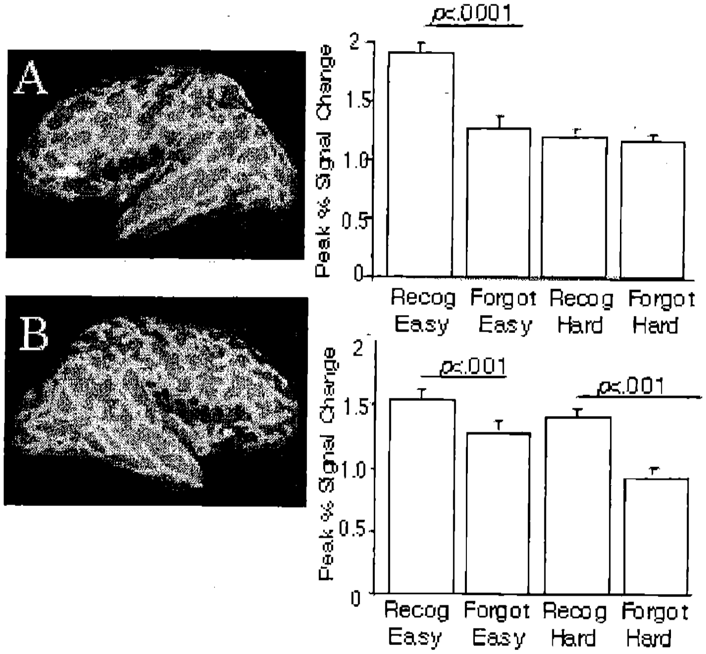

Figure 2. Effect of auditory task difficulty on activation at encoding: A region of left ventrolateral prefrontal cortex (BA 44) showed a smaller peak percentage signal change during encoding with the hard task (2.1) than with the easy task (2.5; p<.001).

To assure that this difference was due to differences in the encoding processes, rather than to differences in the neural processes recruited for the auditory discrimination task, we conducted a control experiment in which 9 participants performed only the auditory discrimination tasks. Voxel-based and ROI analyses indicated no modulation in PFC or the MTL as a function of the difficulty of the secondary task. The only regions that showed significant modulation (p<.01 uncorrected) were the anterior cingulate gyrus (BA31) and primary auditory cortex (BA 41, 42); these regions showed greater activation during performance of the hard task than the easy task.

The finding that the PFC reductions in activation were not related solely to the difficulty of the secondary task supports our hypothesis, and that proposed by prior researchers (Fletcher et al., 1995; Shallice et al., 1994; Iidaka et al., 2000), that the reductions in activation stem from differences in encoding processes carried out with the two secondary tasks. What, then, are the neural processes that support successful encoding with the hard task and the easy task?

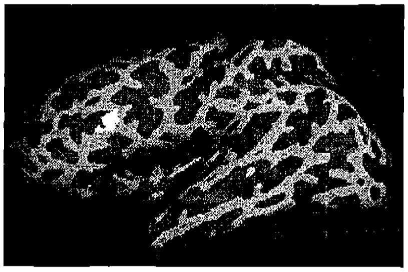

Figure 3. PFC activation at encoding related to retrieval success: Two regions showed activation related to subsequent memory. The left inferior PFC (BA 45/47; A) showed this effect only for items encoded with the easy task; the right inferior PFC (BA 45; B) showed the relation for items encoded with either the easy or the hard task.

Functional MRI Results: Subsequent Memory

To address this question, we conducted analyses of subsequent memory (as in Wagner et al., 1999; Kirchhoff et al., 2000; Davachi et al., 2001; Otten & Rugg, 2001; Otten & Donchin, 2000; Fernandez et al., 1999; Brewer et al., 1998). ROIs defined from the contrast of all encoding trials versus baseline indicated four regions that showed subsequent memory effects (i.e., greater signal change for subsequently remembered items than for subsequently forgotten items): two areas in PFC, one in left inferior PFC - BA 45/47 (Figure 3a) and one in right inferior PFC - BA 45 (Figure 3b), and two regions of the MTL, the anterior left hippocampus (Figure 4a) and the left inferior middle parahippocampal gyrus (Figure 4b). In prior studies, activation in these regions, particularly the left PFC and MTL areas, also predicted subsequent memory (Wagner et al, 1999; Kirchoff et al., 2000; Davachi & Wagner,2002; Otten & Rugg, 2001; see Paller & Wagner, 2002 for review).

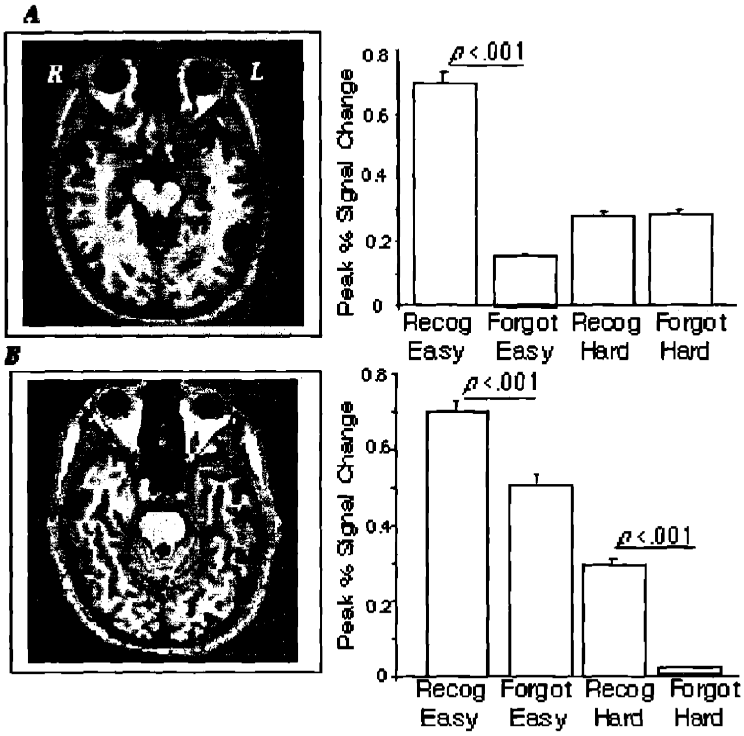

Figure 4. MTL activation at encoding relative to retrieval success: Two regions showed activation related to subsequent memory retrieval. The left anterior hippocampus (A) showed the effect only for items encoded with the easy task, whereas the left parahippocampal gyrus (B) showed the relation for items encoded with either task.

We then analyzed the activation in these ROIs to examine whether it related to successful encoding (i.e., subsequent correct recognition) for items encoded with the easy and the hard auditory task, or only for items encoded in one of these conditions. The peak percentage signal change (relative to baseline) in the left inferior PFC region (BA 45 and 47) predicted successful retrieval only for items encoded with the easy auditory task (Figure 3a). Activation in this region did not differ for subsequently remembered versus forgotten items encoded with the hard auditory task. The findings were different for the area in right inferior PFC (BA 45; Figure 3b). Here, activation predicted subsequent memory for items encoded with the easy task, as well as for items encoded with the hard task.

Within the MTL, left anterior hippocampal activation (Figure 4a) correlated with subsequent retrieval success only for items encoded with the easy task. In contrast, activation in the left inferior middle parahippocampal gyrus (Figure 4b) predicted retrieval success for items encoded with either the easy or the hard task.

The results of the subsequent memory analyses indicated that the locus of signal change at encoding that predicted retrieval success for items encoded with the hard task comprised a subset of the areas where activation changes predicted retrieval success for items encoded with the easy task. These data together with the finding from the behavioral study that participants did not encode as much detailed information with the hard task suggest that the formation of detailed, recollective memories depends on the left inferior PFC and left anterior hippocampus.

fMRI Results, Effects of Encoding Condition on Regions Recruited during Successful Retrieval

If, as the behavioral companion study and subsequent memory analyses suggested, participants formed qualitatively different types of memories for items encoded with the hard as compared to the easy auditory task, it is possible that different brain regions were brought on-line during the retrieval of these traces.

Successful Retrieval: ROI Analyses

To address this issue, we defined ROIs based on the contrast of all retrieval (easy and hard) versus baseline. We then examined which of those regions showed greater activation during correct retrieval as compared to incorrect retrieval. Four brain regions met this criterion. One region in right inferior PFC (BA 44; Figure 5a) showed greater activation during retrieval of words encoded with the hard task as compared to retrieval of words encoded with the easy task. This finding, together with the behavioral companion study data showing that memory traces lacking in detail occurred more frequently for items encoded with the hard versus the easy task, implicates right inferior PFC as a component of the substrate for the sense of "knowing" or "familiarity."

Two regions in left PFC (BA 45 and BA 9 and 44; Figures 5b and 5c) showed the opposite pattern: greater activation during retrieval of words encoded with the easy task. This result, together with the behavioral result that participants retrieved detailed memories more frequently for items encoded with the easy versus the hard task, identifies left PFC regions as part of the circuit underlying retrieval of detailed, recollective memories.

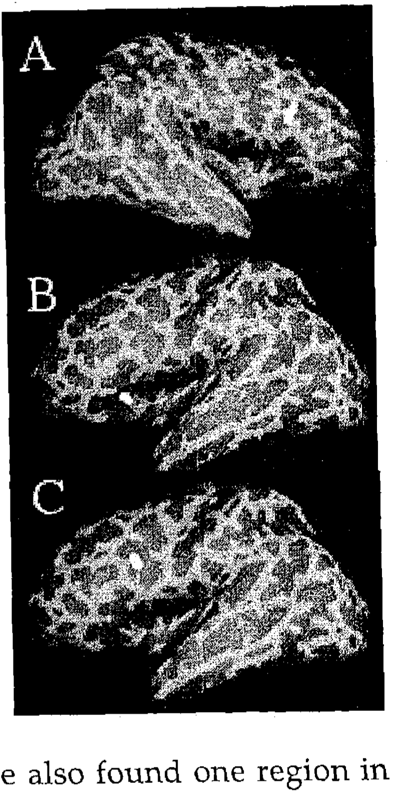

Figure 5. Prefrontal activation during <u>successful retrieval</u> related to encoding difficulty: A right inferior PFC region (BA 44; 43, 17, 24; A) showed greater activation during correct retrieval of words encoded with the hard task (1.5) as compared to the easy task (1.2). Two regions of left PFC (BA 45; -38, 28,2; B) and BA 9/44; -41, 13, 25; C), in contrast, showed greater percentage signal change during retrieval of items encoded with the easy vs. the hard task (1.0 and 0.75, respectively, for region B, and 1.6 and 1.3, respectively, for region C, $p<.001$).

We also found one region in the left anterior hippocampus that showed greater activation during the retrieval of words encoded with the easy versus the hard task (Figure 6). This finding is consistent with recent literature (Aggleton &

Brown, 1999; Davachi et al., 2001; Brown & Aggleton, 2001; Eldridge et al., 2000; Strange et al., 2002) indicating that the hippocampus specifically supports in the retrieval of recollective, but not familiarity-based, memories. Despite recent claims that the parahippocampal gyrus is activated above baseline during retrieval of familiarity-based memories (Yonelinas et al., 2001; Davachi et al., 2001; Strange et al., 2002), we found no parahippocampal activation during retrieval.

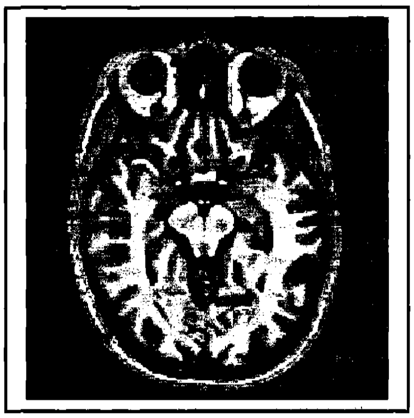

Figure 6. Medial temporal-lobe activation during <u>successful retrieval</u> related to encoding difficulty: The left anterior hippocampus showed similar modulation as the left prefrontal regions: greater percentage signal change during retrieval of items encoded with the easy (.57) than with the hard (.17) task ($\underline{p}<.001$).

DISCUSSION

The motivation for this study was the finding that although the neural activation during encoding was reduced by divided attention (Fletcher et al., 1995; Shallice et al., 1994; Iidaka et al., 2000), individuals can, nevertheless, learn information when their attention is divided. The event-related design of this study allowed us to assess which brain regions support successful memory formation (i.e., successful encoding) when participants performed a hard or an easy secondary task. We also investigated whether the regions recruited for successful retrieval of information differed depending on whether that information had been learned with the hard task (favoring familiarity) or with the easy task (favoring recollection) at encoding.

Before addressing these two questions, we asked whether our divided attention manipulation, like those used in prior PET studies (Fletcher et al., 1995; Shallice et al., 1994; Iidaka et al., 2000; Anderson et al., 2000), resulted in reductions in activation in regions implicated in episodic encoding. Consistent with prior PET studies, we found that encoding with the hard versus the easy distractor task reduced the activation in various PFC regions, including a region in the left ventrolateral PFC believed to play a role in maintenance of verbal information (Poldrack et al., 1999).

Like prior researchers (Fletcher et al., 1995; Shallice et al., 1994; Iidaka et al., 2000), we interpreted this reduction in activation as reflecting a degradation of encoding processes when participants performed the hard concurrent task. This view is consistent with the behavioral companion study reported here, and with extensive behavioral evidence that divided attention at encoding reduces the probability of successful retrieval (Craik et al., 1996; Naveh-Benjamin et al., 2000a; Naveh-Benjamin et al., 2000b), and in particular, reduces the ability to form rich, "recollective" memories (Yonelinas, 2001). It is also possible that encoding items with a hard secondary task reduces the explicit memory traces formed, forcing increased reliance on neural substrates supporting implicit memory formation (Fletcher et al., 1995; Shallice et al., 1994).

The convergence of our results using a constrained encoding task (i.e., "Decide whether each word is abstract or concrete") with those of prior PET studies using unconstrained encoding tasks (e.g., "Learn these word pairs") and cued recall (e.g., providing the first word of a word pair), suggests that the functional neuroimaging results generalize to a range of intentional encoding tasks. It will be worth examining in future studies whether this effect also generalizes to incidental encoding tasks (i.e., when participants are not aware that a memory task will follow).

What Brain Regions Support Successful Memory Formation?

We then investigated what brain regions supported successful encoding (i.e., encoding of items that participants later recognized correctly) in the hard task and the easy task. Previous research on encoding with full attention showed a relation between successful encoding and magnitude of activation in the left PFC (Wagner et al., 1999; Johnson et al., 1997), hippocampus, and parahippocampal gyrus (Brewer et al., 1998; Kirchhoff et al., 2000; Wagner et al., 1999; Fernandez et al., 1999). Our results converge with these findings: Bilateral inferior PFC (left BA 45/47, right BA 45), the left anterior hippocampus, and the left inferior middle parahippocampal gyrus all showed subsequent memory effects for items encoded with the easy task. Only a subset of these regions (right inferior PFC and left parahippocampal gyrus), however, related to subsequent memory for items encoded with the hard task. The regions that no longer supported successful encoding are regions that appear to be tied to the formation of detailed, recollective memories (Davachi et al., 2001; Strange et al., 2002), whereas the regions that continued to support successful encoding even with the concurrent hard secondary task are those that have been linked to formation of less detailed memories that evoke a "sense of knowing" or "familiarity" (Davachi et al., 2001; Strange et al., 2002). Our fMRI results, therefore, are consistent with the behavioral evidence presented here: Participants are more likely to form detailed memories for items encoded with the easy task than with the hard task.

What Brain Regions Support Successful Retrieval?

We hypothesized that brain activation at retrieval could differ when retrieving qualitatively different memory traces (i.e., for detailed memories encoded with the easy task, versus less detailed memories encoded with the hard task). Consistent with this hypothesis, we found a dissociation between the regions used to retrieve items encoded with the easy and with the hard task. In particular, we found greater activation in left PFC regions (BA 45; BA 9/44) for correctly retrieved items that had been encoded with the easy as compared to the hard task, and greater activation in a right PFC (BA 44) region for items that had been encoded with the hard as compared to the easy task. These laterality effects are consistent with recent neuroimaging studies suggesting that right-sided regions may be recruited when individuals are asked to make recognition judgments based on familiarity (Dobbins et al., 2003; Henson et al., 1999; Henson et al., 2000), as may occur when memory traces are not detailed and include only familiarity information. In contrast, left-sided regions appear more important for retrieval of memories with rich detail (Johnson et al., 1997; Ranganath et al., 2000; Nolde et al., 1998a, 1998b; Rugg et al., 1999).

A question has remained about whether these laterality effects represent differences in retrieval orientation (i.e., whether participants are attempting to retrieve or to monitor for detailed information or familiarity information) or differences in retrieval success (i.e., whether the products of the retrieval effort include recollective information or familiarity information). Our data support the interpretation that the laterality effects are based on differences in retrieval success. The retrieval scans intermixed items that had been encoded with the easy and hard tasks; thus, participants did not know the condition under which specific items had been encoded. It is, therefore, difficult to imagine that participants adopted different retrieval strategies for words encoded with the different tasks. It seems more plausible that the observed laterality effects were based on the qualitative nature of the memory trace that was retrieved (i.e., the amount of detail present). In other words, these results suggest that when different types of memory traces are formed at encoding (e.g., recollective versus familiarity-based; or explicit versus implicit, as proposed by Fletcher, Shallice and colleagues; Fletcher et al., 1995; Shallice et al., 1994), different brain regions may be brought on-line later to allow the successful retrieval of those items.

It is unclear why these laterality effects occur: It is possible that right PFC regions are used during post-retrieval monitoring, and thus are more critical for items with weaker traces, where they are closer to the boundary between what a person will accept as "old" versus assign as "new" (Henson et al., 2001; Yonelinas, 2002). Right prefrontal specialization is also found in studies of novelty (Menon et al., 2000), and a familiarity-based signal may be similar to that required for determining whether an object is novel. The left-sided activation found in the present study could result from semantic processing of the words; however, even studies with nonverbal stimuli have found left-sided prefrontal activation during retrieval of detailed information (Ranganath et al., 2000).

Conclusion

Using a divided attention paradigm, we found that participants' memories of words encoded with a easy secondary task were more detailed ("recollective") than those encoded with a hard task. A greater proportion of the words encoded with the hard task than the easy task relied on a less detailed "sense of knowing" or "familiarity." Functional MRI indicated that encoding with the hard task showed less activation in PFC regions associated with episodic memory formation than encoding with the easy task. Only a subset of the brain regions that supported successful encoding with an easy secondary task continued to do so when encoding occurred with a hard secondary task. Activation in left inferior PFC and the left anterior hippocampus predicted retrieval success only for items encoded with the easy task, whereas activation in right inferior PFC and left inferior middle parahippocampal region predicted retrieval success for all items. Divided attention at encoding also affected the neural processes recruited for successful retrieval: We found a dissociation between brain regions preferentially used to retrieve items encoded with the easy task (left PFC and left anterior hippocampus) and those used with the hard task (right PFC). These results suggest that the brain regions that support successful encoding and successful retrieval vary depending on the detail of the memory trace. "Familiarity"-based traces lacking in detail may rely on right-sided PFC, whereas "recollective" traces that are rich in detail may rely more on left-sided PFC and the hippocampus.

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Chapter 2

Memory Enhancement for Emotional Words: Are Emotional Words More Vividly Remembered than Neutral Words?

Individuals are more likely to remember negative information than neutral information. The experiments reported here examined whether individuals were also more likely to remember details of the presentation of negative words, as compared to neutral words. Experiment 1 used the "remember"-"know" procedure to examine the effect of emotion on the vividness of an individual's memory, finding that "remember" responses were more frequently assigned to negative words as compared to neutral words. Experiment 2 used a source memory paradigm, and again found evidence that individuals' memories about the details of a words presentation were more accurate for negative as compared to neutral words. Experiments 3-6 examined the relative contribution of valence and arousal, finding that both dimensions increased the vividness of remembered information (i.e., items with only valence, and those which elicited arousal, were better remembered than neutral information), but that the effect was greater for words that evoked arousal versus those with valence only. The results support a qualitative, as well as a quantitative memory benefit for emotional as compared to neutral words.

Observations in everyday life provide abundant evidence that facts and events associated with strong emotions are better remembered than those lacking emotional richness. The extreme of this effect has been demonstrated in investigations of "flashbulb memories" where individuals retain a vivid, almost photographic, memory of an emotional event (Rubin & Kozin, 1984; Neisser & Harsch, 1992; Heuer & Reisberg, 1990). Although flashbulb memories are formed only in rare occasions, experiences in daily life are often infused with emotional relevance. These emotional, autobiographical memories are more likely to be recalled than autobiographical events that lack emotional significance. In addition, these events are often remembered with better detail, or with enhanced vividness, than are memories void of emotional import (Conway, 1990; Pillemer, Rhinehart, & White, 1986).

A plethora of laboratory studies have confirmed that individuals are more likely to remember emotional than neutral information. Thus, if participants are shown a series of emotional and neutral stimuli, they will later recall or recognize a greater proportion of the emotional stimuli than the neutral stimuli. This emotional memory enhancement effect has been replicated in studies using pictures, words, sentences, and narrated slide shows (see Buchanan & Adolphs, 2003; Hamann, 2001 for reviews). These studies, focusing on the quantatitative memory benefit for emotional versus neutral information, however, have neglected to address a critical feature of flashbulb memories, and memories for other real-life emotional events: Not only are people more likely to remember this emotional information than they are to remember neutral information, they also feel that their memories for these emotional events are particularly vivid, and contain more contextual detail than is typically the case for memories of neutral events. For example, the hallmark of a flashbulb memory is not the ability to remember simply that the event occurred, but rather, the capacity to retain contextual information, such as where a person was, or what they were wearing, upon first learning of the event (Rubin & Kozin, 1984; Nisser & Harsch, 1992).

RECOLLECTION AND FAMILIARITY AS PROCESSES CONTRIBUTING TO RECOGNITION

Before returning to this observation, it is first necessary to briefly discuss the literature suggesting that recognition responses may not rely on monolithic processes. Rather, recognition of some items may be based on a detailed, vivid feeling of re-experience (recollection), whereas other items may be recognized based on a sense that the items has been previously encountered (a sense of familiarity).

Recollection is typically equated with the types of processes that are believed to allow correct recall: item-specific information that includes details surrounding the item's presentation. Familiarity, in contrast, lacks this kind of detail, and instead is a feeling of recent encounter with an item. Recollection is thought to be a slower, attention-demanding process, whereas assessments of familiarity are faster and more automatic.

Recollection and familiarity can be distinguished when participants are asked to determine whether they "remember" or "know" stimuli from a list (Gardiner & Java, 1993; Tulving, 1985). A "remember" response signifies that the individual has a specific memory of the item's presentation, including such information as where it occurred in the list, or an association made with the item. In contrast, a "know" response indicates that an individual has a sense that the item was previously encountered, but lacks any detailed information about its presentation. Recent neuroimaging evidence suggests that the processes contributing to "remember" and "know" responses may rely on dissociable prefrontal and medial temporal-lobe networks, with processes leading to "remember" responses recruiting left-lateralized prefrontal regions and the hippocampus, and processes leading to "know" responses supported by right-lateralized prefrontal regions and the parahippocampal gyrus (e.g., Mark & Rugg, 1998; Henson, Shallice, & Dolan, 1999; Henson, Rugg, Shallice, Josephs, & Dolan, 1999; Kensinger et al., 2003; Davachi & Wagner, 2002; Davachi, Mitchell, & Wagner, 2003).

Rather than assume that "remember" and "know" map directly onto the constructs of recollection and familiarity as was initially proposed (e.g., Gardiner & Java, 1993), recent theorists (e.g., Jacoby, Yonelinas, & Jennings, 1997; Yonelinas et al., 1998) have suggested that recollection and familiarity are independent or orthogonal processes, in contrast to "remember" and "know" responses, which are mutually exclusive. In an experimental setting, "remember" and "know" are mutually exclusive, because an individual is instructed to give a "know" response only when he or she does not have the detailed information that would allow a "remember" response. In reality, however, recognition may often be based on some combination of recollection and familiarity processes; thus, the two processes may not be mutually exclusive. Further, the extent to which recognition for an item is driven by recollection may be independent from the extent to which it is driven by familiarity (e.g., an individual could have a lot of recollection, but little familiarity, or a lot of recollection and familiarity, or any possible combination). Thus, the two processes may be independent. Because we wished to be agnostic about issues related to exclusivity (as assumed in the "remember" or "know" scoring) versus independence (as may characterize the relation between recollection and familiarity), the present research uses "remember" and "know" responses, as well as estimates of recollection and familiarity (calculated as suggested by Yonelinas et al.,1998[4]), to address how attention modulation affects the richness of memories for negative as compared to neutral items.

RECOLLECTION BENEFIT FOR NEGATIVE STIMULI

Returning to the emotional memory literature, there is reason to believe that individuals may show an enhanced tendency to recollect emotional as compared to neutral information. In addition to the studies of real-life events mentioned earlier, there have also been a couple of laboratory studies suggesting that the ability to recollect (Ochsner, 2000) or to remember contextual details (Doerksen & Shimamura, 2000) may be enhanced by the presence of emotional significance. Ochsner (2000) demonstrated that individuals were more likely to recollect negative as compared to neutral pictures, while their ability to sense that the photograph was familiar was less affected by the emotional content of the pictures. He hypothesized that this recollective benefit for negative stimuli

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[4] Recollection is computed by subtracting the proportion of remember false alarms (Rnew) from remember hits (Rold) and then dividing by the proportion of times a participant could have responded remember correctly (1-Rnew). Familiarity is calculated by first computing the probability of correctly responding know to an old item (Fold) and of incorrectly responding know to a new item (Fnew). These values (Fold and Fnew) are calculated based on the assumption that a K response can be given only when an item is familiar but cannot be recollected (i.e., Fold = Kold/(1-Rold) and Fnew = Knew (1-Rnew).

results from increased distinctiveness at encoding for these items (i.e., the encoding of item-specific features that have minimal or no overlap with those of other presented items). Doerksen and Shimamura (2001) showed that source memory (thought to rely on recollective processes) is better for negative words than for neutral words. They suggested that this improved source memory may be due to enhanced autobiographical elaboration for the negative as compared to the neutral words. A study of false memories (Pesta et al., 2001) has also supported the conclusion that emotional (taboo) information has greater distinctiveness: Individuals were less prone to falsely recognize emotional lures than nonemotional lures, likely because of the increased distinctiveness associated with the emotional items.

CONTRIBUTIONS OF VALENCE AND AROUSAL

In a widely-accepted psychological model of emotion, valence (how positive or negative a stimulus is) and arousal (how calming or exciting a stimulus is) are postulated to be orthogonal dimensions in whose space all emotions lie (e.g., Russell, 1980; Lang, Greenwald, Bradley, & Hamm, 1993). In all of the prior studies examining whether emotional information was remembered in more detail than neutral information, the chosen stimuli contained both valence and arousal. Thus, the relative contributions of of the two dimensions (arousal and valence) remain underspecified. Ochsner (2000) hypothesized that the dimension of arousal may have been particularly important. He proposed that some of the distinctiveness provided by emotion stemmed from the physiological responses resulting from the stimuli. Clearly, emotional arousal is a critical mediator of the memory enhancement effect for many types of information: Pharmacological (e.g., Cahill, Prins, Weber &

McGaugh, 1984) and stimulus (e.g., Cahill & McGaugh, 1995; Bradley, Greenwald, Petry, & Lang, 1992) manipulations which increase arousal levels also enhance subsequent memory performance.

There is also evidence, however, that items with valence, but lacking in arousal, can be better remembered than neutral information (e.g., Ochsner, 2000; Kensinger et al., 2002). This enhancement could result from an increased likelihood for individuals to elaborate on items with valence (either activating semantic or autobiographical information), which could also lead to an enhancement in the ability to vividly recollect these stimuli (i.e., because these items would then have also been encoded in a more distinct fashion than neutral stimuli). In contrast, these items could also be better remembered based on distinct processes (e.g., an increased ability to judge the item as "familiar"). The experiments in the present study first confirmed the presence of the recollective (Experiment 1) and source memory (Experiment 2) enhancements for words that were both negatively valenced and arousing. The relative contributions of valence and arousal to the effect were then investigated (Experiments 3-6).

EXPERIMENT 1: VIVIDNESS OF MEMORIES FOR NEGATIVE AND NEUTRAL WORDS

Words create an interesting follow-up to the results of Ochsner (2000), because words have fewer attributes associated with them, and thus are often encoded less distinctly than pictures (Dewhurst & Conway, 1994; Rajaram, 1993). Words also are easier than pictures to match on a range of dimensions (e.g., frequency, familiarity) that affect memory performance; pictures are more difficult to match for degree of unusualness, visual complexity, and other features that could contribute to distinctive encoding. The goal of Experiment 1 was to assess whether the recollection benefit reported for negative pictures (Ochsner, 2000) would also be present for negative words.

Methods

Participants

Participants comprised 18 male MIT undergraduate or graduate students (ages 18-30 years, mean = 21.5; 13-18 years of education, mean = 15.1). Participants gave informed consent and received $10/hour for their participation. All participants were right handed, native English speakers. No participant was taking centrally acting medications, had a history of mental illness or depression, or was currently depressed.

Design and Materials

We selected as stimuli 280 words from the Affective Norms for English Words (ANEW; Bradley and Lang, 1999). One-half of the words were neutral, and one-half were negative. Negative words were selected to be low in valence and high in arousal. These words have been classified reliably in terms of valence and arousal, and Bradley and Lang (1999) have shown that these ratings correspond to physiological changes.

Neutral and negative words were matched pairwise for word frequency, word familiarity, word length, and imageability (Kuchera & Francis, 1967; Coltheart, 1981). They were also matched for the number of abstract versus concrete words. The 280 words were divided into two sets of 140 (70 neutral, 70 negative) words. The sets that served as the study list versus the non-studied foils on the recognition test were counterbalanced across participants. Words were presented in Geneva, 48-point black font on a Macintosh laptop computer for 2 sec each, and in a pseudorandom order. Each participant viewed one study list.

Procedure

All participants completed one testing session lasting approximately 45 min. At the beginning of the study session, participants were told that they were going to see a series of words, and that they should rate each word as "abstract" or "concrete" by making a button press with their right middle or right ring finger, respectively. They were informed that after completion of the study list, they would be given a recognition test.

A self-paced recognition test occurred after a 15-min delay. Participants were asked to select whether they vividly "remembered" the word from the list, "knew" the word was familiar and believed it had been previously presented, or thought that the word was "new" (not previously presented).

After completion of the study-test cycle, participants rated all words (including foils on the recognition test) on a 1-9 scale for valence (1=highly negative; 9=highly positive) and a 1-9 scale for arousal (1= highly calming; 9 = highly arousing; Table 1). These ratings were used to classify the items as negative or neutral for each participant. Separate analyses were conducted using median split of valence ratings to divide words into neutral and negative, or using cut-off points (valence of 1-3 for negative, valence of 4-7 for neutral). These methods revealed a very similar grouping of words as negative or neutral, and all the presented data used the cut-off system. There was little inter-participant variability in whether a word was rated as negative or neutral. The selection of the words was such that the emotional words were both arousing and low in valence (i.e., negative).

Table 1. Valence and arousal ratings of stimuli used in Experiments 1 and 2 (mean, SD).

Item Type	**Mean Rating (max = 9)**	
	Set A	**Set B**
Negative		
Valence[a]	1.78 (.63)	1.91 (.61)
Arousal[b]	6.95 (.53)	7.16 (.72)
Neutral		
Valence	5.83 (.47)	5.65 (.43)
Arousal	3.12 (.93)	3.35 (.87)

a Valence: 1 = highly negative, 9 = highly positive

b Arousal: 1 = highly calming, 9 = highly arousing

Data analysis

Data were analyzed in two ways. First, we calculated the corrected recognition scores (% "remember" hits - % "remember" false alarms or % "know" hits - % "know" false alarms). False alarm rates were computed separately for negative and neutral words; however, because these false alarm rates did not differ, we collapsed across foil type when computing the corrected recognition scores.

Second, we computed recollection and familiarity scores as suggested by Yonelinas et al. (1998). These scores take into account the fact that the probability of making a "know" response to a presented word is constrained by the number of "remember" responses made to presented words because participants were instructed to respond "know" to items that are familiar and not recollected.

Analyses consisted of repeated-measures ANOVA with item type (negative, neutral) and memory strength ("remember," "know"; or recollection, familiarity) as within-subject factors, and subsequent *t* tests. All reported p values are two-tailed.

Table 2. Experiment 1: Memory performance as a function of item type (mean, SD).

Item Type	**Corrected Recognition**			
	Remember	**Know**	**Recollection**	**Familiarity**
Negative	.47 (.22)	.16 (.23)	.50 (.25)	1.6 (.80)
Neutral	.25 (.20)	.25 (.23)	.28 (.23)	1.2 (.72)

Results

Corrected Recognition Scores

Repeated-measures ANOVA indicated a significant effect of item type (Table 2). T tests confirmed that participants' memory was better for negative than for neutral words [t(17)= 4.14, p < .01]. This enhancement was present in 16 of the 18 participants.

Remember and Know Responses

Repeated-measures ANOVA conducted on the corrected recognition scores (% hits - % false alarms) indicated a marginally significant effect of item type, with individuals recognizing more negative than neutral words [F(1,17) = 3.09, p<.10], a significant effect of memory strength, with individuals giving more "remember" than "know" responses [F(1,17) = 34.62, p<.001], and a significant item type x memory strength interaction [F(1,17) = 40.60, p<.0001].

T tests indicated that the interaction stemmed from participants giving a significantly greater proportion of "remember" responses to negative versus neutral words [t(17) = 7.32, p<.001], but a greater proportion of "know" responses to neutral than negative words [t(17) = 4.05, p<.01]. The effects were remarkably consistent across participants: All 18 participants responded "remember" to a greater proportion of negative than neutral items.

Recollection and Familiarity

Repeated-measures ANOVA conducted on the recollection and familiarity scores showed a main effect of response type, with familiarity scores being higher than recollection scores [F (1,17) = 47.31, p<.001], a main effect of item type, with both scores being higher for negative than neutral items [F (1,17) = 10.17, p<.01], and no interaction between memory strength and item type [F (1,17) = .47, p>.5]. Subsequent t tests indicated that recollection was higher for negative than neutral stimuli [t (1, 17) = 7.29, p<.001], and familiarity was marginally higher for negative than neutral words [t (1,17) = 1.90, p <.10]. Again the recollection enhancement was present in all 18 participants.

Discussion

Experiment 1 indicated that recognition memory was better for negative as compared to neutral words. This finding is consistent with prior studies that found memory enhancement for emotional as compared to neutral stimuli (see Hamann, 2001, for review), including on tests of recognition (Kensinger et al., 2002; Ochsner, 2000). This general enhancement effect was relatively consistent, occurring in 16 of 18 participants.

Although this finding is interesting on its own, prior studies have found such enhancement effects, and have found them in the majority of their participants (see Hamann, 2001, for review). The novel question addressed by Experiment 1 was whether the enhancement effect would stem from increases in recollection (or "remember" responses), or familiarity (or "know" responses). When participants' "remember" and "know" responses were analyzed, the enhancement effect appeared to be dominated by the increase in "remember" responses: Participants gave a significantly greater proportion of "remember" responses to negative than to neutral words. This result suggests that vivid, detailed memories were formed more frequently for negative items than for neutral items. Importantly, this enhancement effect was reliable across participants: All 18 individuals gave a greater proportion of "remember" responses to negative than to neutral words. The results from the analyses computing recollection reached a similar conclusion: All 18 participants were more likely to use recollection when recalling negative as compared to neutral words. These results confirm that the "remember" or recollection responses are greater to negative items, suggesting that individuals are better able to conjure a detailed memory for a negative as compared to a neutral event.

This conclusion does not rule out the possibility that individuals may also have a greater sense of familiarity for negative than neutral items. A number of studies have found increased fluency for emotional items (Bargh, Chaiken, Govender, & Pratto, 1992; Kitayama, 1990; Williams et al., 1996), suggesting that processes contributing to familiarity may indeed be greater for emotional than neutral items. Consistent with this conclusion, familiarity responses were greater for negative than neutral items. It is important to point out that the results of the familiarity analyses diverged from those of the "know" responses: familiarity was greater for negative items, while "know" responses were given more frequently to neutral items. This discrepancy is likely due to the fact that the "remember" and "know" procedure requires participants to make a "know" response only when the item is recognized but not "remembered" (i.e., "remember" and "know" are mutually exclusive). Familiarity responses, which take into account the fact that recollection and familiarity can drive a correct recognition response jointly, were found to be marginally larger for negative than neutral items, suggesting that negative items are both more richly remembered, and more frequently sensed to be familiar. The finding of increased familiarity toward negative items is consistent with some prior memory studies (e.g., Ochsner, 2000), and indicates that individuals recognize negative words better due to increases in recollection and familiarity.

In summary, Experiment 1 showed that memory is enhanced for negative as compared to neutral words. This effect appeared to result from increases in both recollection and familiarity, although the increases in recollection were more consistent across participants (occurring in all individuals tested), whereas the increases in familiarity were less consistent across participants (occurring in 13 of the participants). The results further indicated that even for verbal stimuli, which lack the inherent richness of pictures, and even when emotional and neutral words are matched for characteristics that affect distinctiveness (e.g., frequency, familiarity), memory is still better for emotional as compared to neutral stimuli.

EXPERIMENT 2: SOURCE MEMORY FOR NEGATIVE AND NEUTRAL WORDS

Recollection and familiarity refer to the subjective richness of a memory. As studies with flashbulb memories have shown (Rubin & Kozin, 1984; Neisser & Harsch, 1992; Schmolck, Buffalo, & Squire, 2000), this subjective vividness is not always correlated with the accuracy of the memory. Experiment 2 used a source memory task to test objectively the richness, or contextual details, associated with memory for negative versus neutral verbal stimuli.

Methods

Participants

For Experiment 2, we enrolled 18 male MIT undergraduate or graduate students (ages 18-30 years, mean = 22.7; education = 14-19 years, mean = 15.7). Participants met the same criteria as outlined for Experiment 1.

Design and Materials

Stimuli were the same as in Experiment 1, and the design was identical, except that half of the words were presented in blue font, and half in red font (to provide source information).

Procedure

The study procedure was identical to Experiment 1, with the exception that participants were told that words would appear in red or blue font, and that the subsequent recognition task would require them to indicate the color of the font for each of the words. The recognition procedure was identical to Experiment 1, except that participants were asked to select "red," "blue," or "new."

Data Analysis

Corrected recognition scores (% hits - % false alarms) were computed to determine item memory. "Hits" were all words correctly recognized as "old" (collapsing across "red" and "blue" decisions). "False alarms" were lures incorrectly called "old" (collapsing across "red" and "blue"). Source memory was calculated as the proportion of presented items not called "new" (i.e., classified as either "red" or "blue") for which the correct color information was selected. Repeated-measures ANOVA with item type (negative, neutral) and memory type (item, source) as within-subject factors were computed, as were subsequent *t* tests. All reported *p* values are two-tailed.

Results

The results showed no bias toward one color or the other in participants' false alarms (48% "red"). We, therefore, did not correct for false alarms when calculating source recognition, but item recognition was corrected for false alarm rate. The false alarm rate was calculated separately for the negative and neutral items; however, because the false alarm rates did not differ, we collapsed across foil type when computing the corrected recognition scores.

Repeated-measures ANOVA indicated a significant main effect of item type [*F*(1,17) = 23.97, *p*<.0001] and memory strength [*F*(1,17) = 70.88, *p* <.0001] and no interaction between item type and memory strength [*F*(1,17) = 2.54, *p* >.1]. Subsequent *t* tests indicated that participants had better item memory [*t*(17) = 4.44, *p*<.0001] and better source memory [*t*(17) = 3.60, *p*<.01] for negative as compared to neutral stimuli (Table 3). As in Experiment 1, the effect was consistent across participants, with 17 of the 18 participants having higher source memory scores for the negative as compared to the neutral items, and 15 of 18 having higher item memory scores for the negative as compared to the neutral items.

Table 3. Experiment 2: Proportion of words correctly identified as old (%hits - % false alarms), and proportion of old items with correct source recognition as a function of item type.

Item Type	**Memory**	
	Item	**Source**
Negative	.70 (.10)	.45 (.16)
Neutral	.63 (.12)	.32 (.16)

Discussion

The goal of Experiment 2 was to assess whether results from a task using an objective measure of the richness of a memory (i.e., naming the color in which the word was written) would converge on the findings of Experiment 1, which found that participants have more detailed memories for negative than for neutral items. The results from the source memory test support this conclusion: Individuals more accurately reported the color of font in which a negative word was presented than the color of font in which a neutral word was presented. This result is consistent with Doerksen and Shimamura (2001), who found source memory enhancement for negative as compared to neutral stimuli, using a similar task design. As in Experiment 1, the enhancement effect was consistent across participants, occurring in 17 of 18 young adults. Also consistent with Experiment 1, item memory, as well as source memory, was superior for the negative items, although this effect was less consistent across participants.

What encoding processes may contribute to this enhancement effect? As discussed in the Introduction, one contributor may be automatic or prioritized processing of negative stimuli. For example, patients with neglect are more likely to notice an emotional stimulus (e.g., a spider) than a nonemotional stimulus (e.g., a flower) presented in their neglected visual field (Vuilleumier et al., 2002; Vuilleumier & Schwartz, 2001). Neuroimaging studies have also shown that the amygdala shows a similar magnitude of activation to fearful stimuli, regardless of whether the stimuli have reached conscious awareness (Vuilleumier, Armony, Driver, & Dolan, 2001; Whalen et al., 1998; but see Pessoa, Kastner, & Ungerleider, 2002). Thus, part of the memory benefit for the negative stimuli used in Experiments 1 and 2 may relate to low-level biasing of attention toward those stimuli.

A second possible factor may relate to elaborative processes. Individuals may be more likely to elaborate on emotional words semantically or autobiographically as compared to neutral words. These elaborative processes could provide the framework for building richer traces, thus contributing to the enhancement effects seen in Experiments 1 and 2.

EXPERIMENT 3: MEMORY ENHANCEMENT FOR WORDS, EFFECTS OF VALENCE AND AROUSAL

The negative words used in Experiments 1 and 2 differed from the neutral words in two dimensions: arousal and valence. These factors may contribute differentially to the emotional memory enhancement effect. Although enhancement effects can result from either valence or arousal (Ochsner, 2000; Kensinger et al., 2002), the memory effects based on valence versus arousal may not be equivalent.

To tease apart the memory enhancement effects due to arousal versus those due to arousal and valence, participants encoded two kinds of words: The first was low in valence (i.e., negative) but not arousing (e.g., sorrow). The second was arousing[5] (i.e., "taboo" words such as sexual body parts or swear words), but arousal and valence were not directly correlated (i.e., words with high absolute valence ratings were not more arousing than those rated as having moderate valence). Experiment 3 asked whether the enhancement effect would exist for words that differed only in valence, and whether the enhancement effect for those items would be as great as for items that also differed in arousal.

Methods

Participants

Participants comprised 20 male[6] undergraduate or graduate students at MIT or Harvard (ages 19-33 years, mean = 21.5; education range = 14-20 years, mean = 15.9). Participants gave informed consent and received $7 for their participation. All participants were right handed, native English speakers. No participant was taking centrally acting medications, had a history of mental illness or depression, or was currently depressed.

Design and Materials

Words included 60 taboo words, 60 negative words, and 60 neutral words. Taboo words were selected to be high in arousal. Negative words were selected

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[5] Physiological measurements taken in our laboratory in a separate group of 20 males, matched in age and education, indicated that the taboo words elicited physiological changes (increased heart rate and blood pressure, [$t(1,19)>2.2$, $p<.05$]), whereas negative, non-arousing words did not.

[6] Men were tested because they have been shown to have greater emotional arousal to sexual information than women (e.g., Murnen & Stockton, 1997) resulting in better memory for this sexual information (e.g., Geer & McGlone, 1990; Lewis et al., 1986).

to be low in valence, and not arousing (Table 4). Neutral words were matched to the taboo and negative words in word length and in the number of abstract and concrete words. Frequency for the taboo words was estimated using an internet search engine (see Blair, Urland & Maa, 2002).

Table 4. Valence and arousal ratings of stimuli used in Experiments 3-6 (mean, SD).

Item Type	Mean Rating (max = 9)
Taboo	
Valence[a]	2.58 (.93)
Arousal[b]	8.02 (.57)
Negative	
Valence [a]	1.78 (.68)
Arousal [b]	3.35 (.79)
Neutral [c]	
Valence	
Arousal	5.22 (.45)
	4.51 (.86)

a Valence: 1 = highly negative, 9 = highly positive

b Arousal: 1 = highly calming, 9 = highly arousing

c Ratings collapse across neutral words from Expts. 3-4 and 5-6 (semantic associates); there were no significant differences in the ratings of these two groups of neutral stimuli.

Methods

Participants were shown 90 words (30 taboo, 30 negative, 30 neutral), one at a time, each for 2 sec. Words were presented on a Macintosh computer screen (Geneva, 48-point font). Participants rated each word as "abstract" or "concrete." Following a 15-min delay, participants took a recognition test in which they indicated whether they vividly "remembered" the word from the word list, "knew" the word was familiar and believed it was previously presented, or believed the word to be "new."

Data Analysis

Repeated-measures ANOVA were conducted with item type (taboo, negative, neutral) and memory strength ("remember"/"know" or recollection/familiarity) as within-subject factors. Subsequent t tests examined the effects of item type and memory strength.

Results

Corrected Recognition

Overall corrected recognition scores (% hits - % false alarms) were first calculated first (Table 5[7]). Overall, corrected recognition was better for the taboo words than the negative words ($t(19)=3.52$, $p<.01$) and for the negative than the neutral words ($t(19)=2.08$, $p<.05$).

Remember and Know

The corrected "remember" and "know" recognition rates were then calculated (Table 5): % "remember" hits - % "remember" false alarms (or % "know" hits - % "know" false alarms). Because the false alarm rate did not differ for taboo, negative, and neutral words (all $p>.5$), the same false alarm rates were subtracted for all item types. Repeated-measures ANOVA conducted on these corrected "remember" and "know" values indicated a significant effect of item type ($F(2,38)=12.06$, $p<.0001$), memory strength ("remember", "know";

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[7] The careful reader may note that performance in Expt 3 is higher than that of Expt 1. This variability in performance likely stems from the fact that participants encoded more words in Expt 1 (140 words) than in Expt 3 (90 words).

F(1,19)=102.52, p<.0001), and a significant interaction between item type and memory strength (F(2,38)=8.85, p<.001). Subsequent t tests confirmed that "remember" responses were greater for the taboo words as compared to the negative words (t(19)=3.82, p<.001), and marginally greater for the negative as compared to the neutral words (t(19)=1.88, p<.08). "Know" responses were similar between all item types (p>.3).

Table 5. Experiment 3: Memory performance as a function of item type (mean, SD).

Item Type	**Corrected Recognition**			
	Remember	**Know**	**Recollection**	**Familiarity**
Taboo	.68 (.16)	.02 (.11)	.63 (.18)	1.3 (0.7)
Negative	.52 (.19)	.06 (.19)	.45 (.22)	.83 (0.9)
Neutral	.39 (.22)	.08 (.14)	.30 (.27)	.80 (0.7)

Recollection and Familiarity

Repeated-measures ANOVA indicated a significant effect of item type (F(2,38)=6.99, p<.01), memory strength (recollection, familiarity; F(1,19)=34.33, p<.0001), and a marginal interaction between item type and memory strength (F(2,38)=2.51, p<.10). Subsequent t tests confirmed that recollection was greater for the taboo words than the negative words (t(19)=3.90, p<.001), and marginally greater for the negative than the neutral words (t(19)=1.92, p<.07). Familiarity was marginally greater for the taboo words than the negative words (t(19)=1.92, p<.07), and significantly greater for the taboo words than the neutral words (t(19)=2.82, p<.01), but did not differ between the negative and the neutral words (p>.8).

Discussion

Experiment 3 examined the enhancement effect for words that differed from the neutral words only in valence versus the effect for words that differed from the neutral words in valence and in arousal. The critical findings were that there was memory enhancement for items that differed in only valence, but that the enhancement was greatest for items differing in arousal and valence. As in the prior experiments, enhancement existed at the level of overall recognition scores, as well as with "remember" responses and recollection. Familiarity was greatest for the taboo words, but was similar between the negative and neutral words. This finding is consistent with literature on fluency enhancement for emotional stimuli; traditionally, the stimuli used have been arousing (Christianson, Loftus, Hoffman, & Loftus, 1991; Williams et al., 1996; Bargh et al., 1992). Thus, valence and arousal appear to boost recollection, whereas arousal (but not valence) may also serve to boost familiarity.

EXPERIMENT 4: EFFECTS OF VALENCE AND AROUSAL ON MEMORY FOR SOURCE

Experiment 3 indicated a difference in the subjective vividness of memories for arousing words, versus for words with valence only. Experiment 4 addressed whether this finding was limited to the realm of subjective ratings, or would extend to a source memory paradigm which allowed for an objective measurement of the contextual details associated with a memory.

Methods

Participants

Participants included 18 males (ages 18-29, mean age = 21.7; years of education = 12-18, mean = 13.5) meeting the criteria outlined in Experiment 1.

Materials and Procedure

Materials were the same as those used in Experiment 3, and the testing procedures were identical to those of Experiment 2. Data were analyzed in the same way as in Experiment 2.

Results

ANOVA indicated a significant effect of item type ($\underline{F}(2,34)=16.71$, $\underline{p}<.0001$), memory strength ($\underline{F}(1,17)=27.51$, $\underline{p}<.0001$), and a marginal interaction between item type and memory strength ($\underline{F}(2,34)=2.50$, $\underline{p}<.10$). Subsequent $\underline{t}$ tests indicated that item memory was marginally better for the negative words than the neutral words ($\underline{t}(17)=1.99$, $\underline{p}<.07$) and similar for the taboo and negative words. Source memory was greater for the negative words than the neutral words ($\underline{t}(17)=2.22$, $\underline{p}<.05$) and greater for the taboo words than the negative words ($\underline{t}(17)=2.49$, $\underline{p}<.05$; Table 6). ANOVA indicated that false alarm rates did not differ for the three item types.

Table 6. Experiment 4: Item and Source Memory Performance (mean, SD) as a Function of Item Type.

Item Type	Memory	
	Item	Source
Taboo	.64 (.15)	.44 (.16)
Negative	.52 (.08)	.31 (.08)
Neutral	.40 (.11)	.25 (.09)

DISCUSSION

The critical findings of Experiment 4 were that participants showed more accurate source memory for the arousing words and words with valence than they did for the neutral words. The magnitude of the enhancement effect was greater for the taboo words than the negative words, as in the prior experiment. Thus, not only do individuals subjectively feel that they have more vivid memories for arousing words or words with valence only, they also perform better on an objective measure of a memory's vividness. The results of Experiments 3 and 4, therefore, indicate that negative valence alone (i.e., without arousal) is sufficient to increase the vividness of a memory; however, the presence of arousal further increases the likelihood of remembering details from an item's presentation.

EXPERIMENT 5: MEMORY ENHANCEMENT, ROLE OF CATEGORY RELATEDNESS

Taboo and negative words can be thought of as categorically related (i.e., "taboo" is a category, as is "negative things." Neutral words, in contrast, have typically been taken from a range of categories, raising the possibility that the memory benefit for the emotional words is not due to their arousal or valence per se, but rather to their categorical relatedness. Experiment 5 addressed this possibility by using neutral words that were all semantic associates.

Methods

Participants

The participants comprised 18 males who were MIT or Harvard undergraduate or graduate students, ages 19-32 years (mean = 27.2) with 14-18 years of education (mean = 16.1). They met the criteria outlined in Experiment 1.

Design and Materials

The materials and design were identical to those of Experiment 3, except that all neutral words were associates of the words "think" or "mind." This selection was chosen because the association is not immediately obvious (i.e., taking all animals would be very easy for participants to notice, and could cause easier discrimination of seen and unseen words than is the case for negative or taboo words). Associates of the words "think" and "mind" also have a similar breakdown between concrete and abstract words as do negative and taboo words[8].

Results

Correct Recognition

Repeated-measures ANOVA conducted on the correct recognition rates indicated a significant effect of item type ($\underline{F}(2,34)=11.28$, $\underline{p}<.0001$). Subsequent $\underline{t}$ tests indicated that memory was better for the taboo words than for the negative words ($\underline{t}(17)=3.87$, $\underline{p}<.001$) or neutral words ($\underline{t}(17)=3.43$, $\underline{p}<.01$), but that memory was similar for the neutral and negative words ($\underline{p}>.5$; Table 7).

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[8] Another group of 18 males was run on an alternate version with neutral words being related to the categories of "household" or "financial." The critical findings replicated those discussed in Experiment 5.

Remember and Know Responses

Repeated-measures ANOVA indicated a significant effect of item type ($F(2,34)=11.28$, $p<.0001$), a marginal effect of memory strength ($F(1,17)=4.14$, $p<.06$), and an interaction between item type and memory strength ($F(2,34)=8.89$, $p<.001$).

Subsequent t tests indicated that "remember" responses were higher for taboo words than for negative words ($t(17)=2.57$, $p<.05$), and were higher for negative than neutral words ($t(17)=3.04$, $p<.01$). "Know" responses were similar for taboo and negative words ($p>.9$), but were higher for neutral than negative words ($t(17)=2.87$, $p<.05$) and for neutral than taboo words ($t(17)=2.19$, $p<.05$). (Table 7).

Table 7. Experiment 5: Memory Performance as a Function of Item Type.

Item Type	**Corrected Recognition**			
	Remember	**Know**	**Recollection**	**Familiarity**
Taboo	.53 (.16)	.24 (.20)	.53 (.16)	2.2 (1.1)
Negative	.38 (.20)	.23 (.19)	.39 (.20)	1.6 (0.9)
Neutral (Semantic Assoc)	.28 (.17)	.34 (.18)	.29 (.17)	1.8 (0.7)

Recollection and Familiarity

Repeated-measures ANOVA indicated a significant effect of item type ($F(2,34)=6.13$, $p<.01$), an effect of memory strength ($F(1,17)=67.47$, $p<.0001$), and no interaction between item type and memory strength ($F(2,34)=1.76$, $p>.15$).

Subsequent t tests indicated that recollection was higher for taboo than negative words ($t(17)=2.56$, $p<.05$) and higher for negative than neutral words (t(17)=3.43, p<.01). Familiarity was marginally greater for taboo than negative words (t(17)=1.80, p<.09), and similar for negative and neutral words (p>.2).

Discussion

The critical finding of Experiment 5 was that the memory enhancement for the negative items remained even when neutral items were semantic associates. Thus, the memory enhancement for the negative items does not appear to be attributable only to the semantic relatedness of the negatively valenced words.

EXPERIMENT 6: RECALL OF WORDS WITH VALENCE AND AROUSAL

Although the results of Experiment 5 reduced the concern that individuals might be using semantic integration to boost their memory for the taboo, or valenced, items, another possible confound was that of word frequency. Although the negative and neutral words were matched for word length and word frequency, the taboo words' frequencies were estimated from an online search. There was a reasonable probability that the taboo words occurred on the internet with more frequency than would be the case in other written texts. It was, therefore, possible that differences in word frequency affected recognition responses. Specifically, as recognition rates have been found to be better for low-frequency words than for high-frequency words (e.g., Mandler, 1980; Kintsch, 1970), it remained possible that the memory benefit for the taboo as compared to the negative or the neutral words resulted from the fact that the taboo words had a lower word frequency.

The effects of word frequency are reversed in recall tasks in which items are grouped into lists of similar frequencies (e.g., Gregg, 1976; Gillund & Shiffrin, 1984). In other words, individuals will typically remember more items from a list of low-frequency words than they will from a list of high-frequency words. Thus, if the memory benefit for the taboo words was due only to differences in word frequency, the reverse effect (i.e., poorer memory for the taboo words) should occur on a recall task.

METHODS

Participants

Participants were 16 males (ages 18-28 years, mean age = 20.7; 12-16 years of education, mean = 13.2). All met the criteria outlined for Experiment 1.

Materials and Methods

Materials were 150 words (50 neutral, 50 with valence only, 50 with arousal), taken from those used in Experiment 5. These materials were divided into 6 lists, each with 25 words of a particular category (e.g., 25 words with arousal). Participants studied one of these lists of 25 words, with each word presented for 2 sec. They judged whether each word was abstract or concrete. Three buffer items were inserted at the beginning and end of the list to control for primacy and recency effects. After viewing the list of words, participants were asked to write down all the words that they remembered from the list. These methods were then repeated until participants had studied one list of words from each stimulus category (i.e., neutral, with valence only, with arousal). The order of the lists, and the lists administered, were pseudorandomized across participants.

Results

ANOVA indicated a significant effect of item type ($\underline{F}(2,28) = 15.16$, $\underline{p}<.001$). Subsequent $\underline{t}$ tests indicated that participants recalled more taboo words than negative words ($\underline{t}(15)=2.88$, $\underline{p}<.05$) or neutral words ($\underline{t}(15)=5.31$, $\underline{p}<.0001$), and more negative words than neutral words ($\underline{t}(15)=3.11$, $\underline{p}<.01$).

Table 8. Experiment 6: Percentage of words recalled as a function of item type (mean, SD)

Item Type	Recall
Taboo	61.3 (18.2)
Negative	45.0 (14.8)
Neutral	36.5 (10.6)

Discussion

Recall rates were higher for items with valence or arousal than for words that were neutral, and the effect was greater for the items with arousal than for those with valence only. Thus, the memory benefit for these emotional categories of words does not appear to be due to word frequency effects; if this factor were the major contributor, than the effect should have been reversed when using a blocked-design recall task as compared to a recognition task. The fact that both recognition and recall rates are higher for words with emotion (valence or arousal) than for neutral words suggests that the memory benefit results from factors independent of word frequency. Additionally, the fact that the memory benefit exists even when neutral words are all semantic associates suggests that categorical similarity (e.g., semantic elaboration based on category membership) is not a sufficient explanation for the memory enhancement effect.

GENERAL DISCUSSION

The present investigation examined whether there was a qualitative memory benefit for emotional as compared to neutral words. The results of six experiments confirm that there is such a benefit: Across all tasks details associated with the presentation of words (assessed through subjective and objective measures) were more likely to be remembered for emotional as compared to neutral items. The benefit emerged for words that only had valence, as well as for words with arousal, although the magnitude of the effect was greater for words with arousal. The effect did not appear to be due to semantic clustering of emotional material, because the effect remained even when neutral words were categorically related. The effect also did not appear to be related to word frequency differences between the arousing and neutral words, because the effects appeared on a recall task as well as on recognition tasks.

This leads to the question of what processes may have contributed to the enhancement effect. As discussed in the introduction, automatic or intentional processes could contribute to the effect. Automatic orienting toward emotional stimuli could allow individuals to be more likely to encode those items. Elaborative processes also likely contribute to the effect: Individuals may be more likely to autobiographically or semantically elaborate on the emotional words. Individuals may also rehearse the emotional words more than the neutral words. Further investigations will be necessary to disentangle the roles of these processes in the enhancement for words with valence only, and with arousal.

In summary, the results of the present study indicate that individuals remember emotional words with more detail than neutral words. Thus, processes that contribute to recollection, or to the formation of source memory, appear to be specifically modulated by the presence of emotion. The effect is strongest when words have arousal, but is also present when words have valence only. These findings extend the results of prior studies by indicating that there is not only a quantitative benefit for emotional information, but also a qualitative one.

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Chapter 3

Memory Enhancement for Emotional Words: Contribution of Automatic and Controlled Processes

Declarative memory is typically better for negative as compared to neutral stimuli. Not only are negative items more likely to be remembered, they also tend to be remembered in more detail than neutral items. The present study employed a divided attention manipulation to uncover the contributions of automatic and controlled encoding processes to the effect. When emotional words were selected that differed from the neutral words in either arousal or valence, the memory for the arousing, but not valence-only words, was resistant to effects of divided attention (Expt. 1). The effect of arousal did not appear to be related only to categorical clustering (Expt. 2). Together, these experiments demonstrate that although recollective enhancement occurs for words with only valence as well as for arousing words, the encoding processes contributing to these enhancement effects differ. Arousing words are remembered in detail due to relatively automatic processes, whereas controlled processes underlie the enhanced ability to remember details about the study episode for words with valence only.

Numerous studies have shown that individuals are more likely to remember negative information as compared to neutral information (Cahill et al., 1995; Phelps, LaBar, & Spencer, 1997; Adolphs et al., 1997; Bradley et al., 1992). In addition, individuals are more likely to remember the details of a negative item's presentation (Ochsner, 2000; Doerksen & Shimamura, 2001; Kensinger et al., 2002; Heuer & Reisberg, 1990). The quintessential example of the enhanced vividness associated with emotional information is a "flashbulb memory." Individuals often retain a detailed memory about the moment when a very emotional event occurred (e.g., the assassination of JFK; Brown & Kulick, 1977). The question that lies at the center of this study is the extent to which attention is required for this recollective memory enhancement for negative stimuli.

Attention-demanding processes are critical for the formation of detailed memories of neutral items. The ability to encode distinctive information appears to be greater when individuals devote attention toward elaborating an item's features (Conway & Dewhurst, 1995; Gardiner & Parkin, 1993) or in "deep" processing of the items' semantic or autobiographical characteristics (Craik & Lockhart, 1972; Friedman & Bourne, 1976; Yesavange & Rose, 1984). This elaboration results from controlled, self-initiated encoding strategies, and these processes are disrupted when individuals must divert resources away from encoding and toward the performance of a secondary task (see Yonelinas, 2002, for review). Thus, dividing a person's attention as they attempt to learn information disproportionately affects the ability to remember details about an item's presentation, while leaving relatively preserved the ability to later recognize that item as familiar (e.g., Yonelinas, 2001).

The aim of the present study was to examine whether the recollective enhancement for negatively emotional information resulted from controlled or automatic processes. It is plausible that emotional information is more vividly remembered than neutral information because it disproportionately engages controlled encoding processes. Individuals may be more likely to elaborate on negatively emotional material, either semantically (Christianson & Engelberg, 1999; Phelps, LaBar, & Spencer, 1997) or autobiographically (Heuer & Reisberg, 1990; Doerksen & Shimamura, 2001). Additional rehearsal of emotional stimuli could also underlie the long-term memory enhancement effect (Christianson & Engelberg, 1999). Any of these controlled processes could lead not only to the increased likelihood of remembering emotional information, but to the enhanced detail associated with those memories for the emotional information.

Alternately, the memory enhancement effect could result primarily from automatic processes, such as automatic orienting toward emotional stimuli or prioritized processing of emotional information. Attentional biases are often found for negative as compared to neutral stimuli (Christianson & Fallman, 1990; Pratto & John, 1991; Williams, Mathews, & MacLeod, 1996). For example, participants made more shadowing errors in a dichotic listening task when highly arousing words were heard in their unattended ear than when less arousing words were presented (Nielsen & Sarason, 1981). Other types of perceptual benefits also appear to exist for negative as compared to neutral stimuli. Negative words are processed faster at a perceptual or conceptual level (Christianson et al., 1991; Loftus, Loftus, & Messo, 1987; Ohman, Flykt, & Lundqvist, 1999; Bargh, Chaiken, Govender, & Pratto, 1992; Williams, Mathews & MacLeod, 1996). Studies of selective attention have shown that individuals are better able to perceive aversive stimuli in a complicated visual display (Ohman, Flykt, & Esteves, 2001), during an attentional blink (Anderson & Phelps, 2001), or while directing attention to another spatial location (Vuilleumier, Armony, Driver, & Dolan, 2001; Vuilleumier & Schwartz, 2001). Taken together, these results suggest that emotional stimuli tend to be given priority for processing.

Neuroanatomically, there has also been recent evidence that the amygdala, the region of the brain thought to mediate the emotional memory enhancement effect (see Hamann, 2001, for review) can respond to emotional stimuli even when attentional resources are limited (e.g., Whalen, 1998; Vuilleumier et al., 2001; but see Pessoa et al., 2002). These results provided further support for the hypothesis that the memory enhancement for emotional information could result from these relatively automatic processes.

A divided attention manipulation provides a way to probe the extent to which the emotional memory enhancement effect is reliant on controlled, attention-demanding processes, as compared to automatic encoding processes. A plethora of studies have indicated that dividing one's attention at encoding hinders subsequent memory (Baddeley, 1984; Craik, Naveh-Benjamin, & Anderson, 2000; Naveh-Benjamin, Craik, Guez, & Dori, 1998; Anderson, Craik, & Naveh-Benjamin, 1998). In particular, divided attention appears to have a large effect on the formation of detailed, recollective memory while having a lesser impact on the ability to encode information that can later drive correct familiarity-based recognition (Yonelinas et al., 2001; Kensinger, Clarke, & Corkin, 2003; see Yonelinas, 2002, for review). It, therefore, seemed particularly useful to examine the effect that divided attention would have on memory for items that tend to be richly remembered (i.e., negative stimuli).

A further goal of this study was to distinguish between items that differ from neutral ones in valence as compared to in arousal. Valence and arousal are traditionally discussed as two independent dimensions of emotion: Valence represents how positive or negative a stimulus is, whereas arousal reflects the extent to which a stimulus is calming or exciting (e.g., Russell, 1980; Lang, Greenwald, Bradley, & Hamm, 1993). Thus, critical to the design of the present experiments, information can be low valence (negative) and high arousal (eliciting a physiological response), or can be low valence (negative) and low arousal (eliciting no physiological response). Although a number of studies have suggested that items with valence show a memory enhancement effect as do items with arousal (e.g., Ochsner, 2000; Lang et al., 1993), the present study examined whether the contribution of automatic and controlled processing were similar for these items types.

Experiment 1: Attention Modulation and Emotional Memory Enhancement: Effects of Valence and Arousal

Using a divided attention manipulation, Experiment 1 examined the contribution of automatic and attention-demanding processes to the memory enhancement for words that differed from neutral words in (a) valence only or (b) arousal. Participants were asked to learn three categories of words (neutral words, words with valence only, and arousing (taboo) words) while performing either an easy auditory discrimination task, a hard auditory discrimination task, or no secondary task. The manipulation of secondary task difficulty allowed examination of the contribution of attentional versus automatic processes to the memory enhancement to negative stimuli.

Methods

Participants

Participants comprised 21 male[9] undergraduate or graduate students at MIT or Harvard (ages 18-32 years; mean = 22.5; education = 14-19 years; mean = 16.3). Participants gave informed consent and received $7 for their participation. All participants met the criteria outlined in Experiment 1.

Design and Materials

Participants studied a list of 180 words (60 taboo, 60 negative, 60 neutral). Taboo words (e.g., swear words, sexual words) were selected to be high in arousal, and to have valences that were not as low as the valence-only, negative, words. Negative words were selected to be low in valence and relatively low in arousal. Taboo, negative, and neutral words were matched for word length and number of abstract or concrete words. Negative and neutral words were closely matched for word frequency and familiarity (Kuchera & Francis, 1967; Coltheart, 1981; Bradley & Lang, 1999) and taboo words were matched, to the extent possible, using an internet search engine estimate of word frequency (Blair, Urland, & Ma, 2002).

One-third of the words were presented with no secondary task; one-third of the words were presented with the easy sound discrimination task; and one-third of the words were presented with the hard sound discrimination task. Six

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[9] Only men were tested because sexual stimuli have been shown to elicit greater emotional arousal in men than in women (e.g., Murnen & Stockton, 1997), and better memory for sexual information (e.g., Geer & McGlone, 1990).

lists were created, counterbalancing the task in which the words were presented (none, easy, or hard auditory discrimination task). The list order was counterbalanced across participants. Study and foil words were also counterbalanced across participants. Auditory sound patterns were created using SoundEdit 16 (Macromedia, Inc). Sounds were 1.5 sec in duration, allowing them to be jittered with respect to the onset of the words (every 2 sec). Sounds were 1.5 sec in duration, to allow them to be jittered with respect to the onset of the words (every 2 sec). Sounds were presented via headphones.

Procedure

All participants completed one testing session lasting approximately 45 min. Participants were instructed to watch as words appeared on the screen (every 2 sec). They rated the words as "abstract" or "concrete". During presentation of one-third of those words, participants listened to auditory stimuli and performed a hard auditory discrimination task. They were asked to press a button every time they noticed that the auditory pattern had changed from Pattern A to Pattern B or from Pattern B to Pattern A. The task was difficult because the two patterns were rhythmically similar and thus hard to discriminate (beep – beep –beep – beep –beep vs. beep – beep – beeeep – beep). The number of times that the auditory pattern changed varied from two to four times per block to prevent participants from anticipating when changes would occur.

During the presentation of another third of the words, participants performed an easy auditory discrimination task. This task was identical to the hard discrimination task, except that these auditory patterns were rhythmically distinct and thus easier to discriminate from one another (beep – beep – beep

–beep –beep vs. ch – beeeep – beep – beeeep, where the "ch" indicates white noise inserted at the beginning of the pattern).[10]. During the remaining third of the words, no auditory stimuli were presented.

The auditory discrimination tasks were blocked, and before each block participants were shown computerized instructions that alerted them to which secondary task to expect (either "No task," "Easy task," or "Hard task"). Although participants were instructed that it was "important to press a button every time the sound pattern changes," debriefing indicated that all participants interpreted the encoding task as the most important task, and the sound task as being of secondary importance.

After a 15-min delay following presentation of each of the lists, participants performed a recognition test with the 180 presented words pseudorandomly intermixed with 180 foils (one-third valence only, one-third taboo, one-third neutral). Participants indicated whether they vividly "remembered" the word from study, "knew" the word was familiar and believed it had been presented at study, or thought the words was a "new" non-presented word.

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[10] There is evidence that the emotional significance of stimuli can be processed relatively automatically, even when attention is directed elsewhere (e.g., Vuilleumier, Armony, Driver, & Dolan, 2001; Vuilleumier & Schwartz, 2001; Anderson & Phelps, 2001). We wanted to be certain, however, that the divided attention manipulations did not affect how individuals perceived the stimuli (i.e., how emotional they interpreted them as being). In a separate study, 21 young adults (ages 18-30) rated stimuli on a scale of 1-9 for valence (1 being highly negative; 9 being highly positive) and arousal (1=calming or soothing; 9 = arousing, agitating, or exciting). We counterbalanced across participants what secondary task (none, easy, hard) occurred with the presentation of each word. No differences in ratings were apparent [all $\underline{t}(1,20)<.43$, $\underline{p}>.3$]. We therefore felt confident that any memory effects present with attention modulation would not reflect differences in how well individuals were able to process the emotional significance of the stimuli.

Data Analysis

Data were analyzed in two ways. First, we calculated the corrected recognition scores (% "remember" hits - % "remember" false alarms or % "know" hits - % "know" false alarms). False alarm rates were computed separately for negative and neutral words; however, because these false alarm rates did not differ, we collapsed across foil type when computing the corrected recognition scores.

Second, we computed recollection and familiarity scores as suggested by Yonelinas et al. (1998). These scores take into account the fact that the probability of making a "know" response to a presented word is constrained by the number of "remember" responses made to presented words because participants were instructed to respond "know" to items that are familiar and not recollected.

Repeated-measures ANOVA with item type (taboo, negative, neutral), memory strength ("remember"/"know" or recollection/familiarity), and task (none, easy, hard) as within-subjects factors were conducted, as were subsequent t tests.

Results

Reaction Times

Participants' response times to the auditory sound changes were significantly slower in the hard as compared to the easy task [$t(20)=2.29$, $p<.05$]. Reaction times did not differ when auditory changes occurred during presentation of arousing, valence-only, or neutral words [$p>.4$]. Participants were slower at classifying words as abstract or concrete during the hard sound discrimination task [$t(20)=2.08$, $p<.05$], although reaction times did not differ for as a function of word type [$p>.3$]. Participants were highly accurate at making the "abstract" or "concrete" decision (fewer than 1% of the responses were errors).

Overall Corrected Recognition

(Collapsing across Remember and Know Responses)

Repeated-measures ANOVA conducted on the overall corrected recognition scores indicated a main effect of task [F(2,40)=9.36, p<.0001], a main effect of item type [F(2,40)=40.76, p<.0001], and no interaction between task and item type (p>.15; Table 1).

Table 1. Experiment 1: Memory performance as a function of item and task type (mean, SD).

		Corrected Recognition			
Task	**Item Type**	**Remember**	**Know**	**Recollection**	**Familiarity**
None	Taboo	.70 (.23)	.00 (.13)	.72 (.25)	1.9 (1.2)
	Negative	.56 (.20)	.11 (.17)	.60 (.22)	2.2 (1.2)
	Neutral	.45 (.26)	.04 (.13)	.56 (.28)	1.3 (1.1)
Easy	Taboo	.62 (.23)	.02 (.13)	.70 (.25)	1.6 (0.9)
	Negative	.42 (.24)	.16 (.18)	.52 (.22)	1.8 (1.0)
	Neutral	.43 (.27)	.07 (.14)	.53 (.26)	1.4 (1.2)
Hard	Taboo	.66 (.23)	.00 (.10)	.72 (.26)	1.9 (1.5)
	Negative	.38 (.22)	.12 (.17)	.48 (.22)	1.3 (0.8)
	Neutral	.30 (.19)	.09 (.13)	.41 (.19)	1.0 (0.8)

Subsequent t tests indicated that overall memory for the taboo words was marginally better than memory for the negative words in the silent task condition (t(20)=1.87, p<.08), and significantly better in the easy task condition (*t*(20)=2.18, *p*<.05) and in the hard task condition (*t*(20)=4.68, *p*<.001). Overall memory for the negative words was better than neutral words in the silent condition (*t*(20)=3.85, *p*<.01), marginally better in the easy condition (*t*(20)=1.76, *p*<.1), and better in the hard condition (*t*(20)=2.36, *p*<.05). The overall enhancement effect for the taboo and negative words, therefore, remained (at least with marginal significance) across all attention conditions.

Remember and Know Responses

Repeated-measures ANOVA indicated a main effect of task (*F*(2,40)=6.3, *p*<.01), item type (*F*(2,40)=14.58, *p*<.0001), and memory strength (*F*(1,20)=53.99, *p*<.0001), significant interactions between task and item type (*F*(4,80)=2.85, *p*<.05), item type and memory strength (*F*(2,40)=4.46, *p*<.05), a marginal interaction between item type and memory strength (*F*(2,40)=2.44, *p*<.1), and a marginal three-way interaction between task, item type, and memory strength (*F*(4,80)=2.10, *p*<.09).

Subsequent *t* tests indicated that "Remember" responses to the taboo words were greater than to the negative words in the silent task (*t*(20)=2.17, *p*<.05), easy task (*t*(20)=4.65, *p*<.0001), and in the hard task (*t*(20)=4.90, *p*<.0001). Marginally more "remember" responses were given to negative as compared to neutral words encoded in the silent task condition (*t*(20)=1.74, *p*<.10), but there was no difference in "remember" responses to negative and neutral items encoded with the easy task or hard task (*p*>.6).

"Know" responses to the taboo words were similar in the silent task and easy task conditions (*p*>.2), but were reduced between the easy and hard conditions (*t*(20)=2.36, *p*<.05). "Know" responses for negative words were unchanged between the silent task and easy task conditions, and between the easy task and hard task conditions ($p > .2$). "Know" responses to neutral words were also similar in the three conditions ($p > .2$)

"Know" responses were fewer for taboo than negative words encoded in the silent task ($t(20)=4.31$, $p < .0001$), easy task ($t(20)=3.74$, $p < .001$), and hard task conditions ($t(20)=5.17$, $p < .0001$). "Know" responses were greater for negative than neutral words encoded with the silent task ($t(20)=2.16$, $p < .05$), easy task ($t(20)=2.18$, $p < .05$), but not the hard task ($p > .3$).

Recollection and Familiarity

Repeated-measures ANOVA indicated significant main effects of task ($F(2,40)=9.36$, $p < .0001$), item type ($F(2,40)=40.76$, $p < .0001$), and memory strength[11] ($F(1,20)=63.88$, $p < .0001$). The analysis revealed no interaction between task and item type ($p > .15$), along with significant interactions between task and memory strength ($F(2,40)=6.60$, $p < .01$), item type and memory strength ($F(2,40)=40.87$, $p < .0001$), and a three-way interaction between task, item type, and memory strength ($F(4,80)=3.33$, $p < .05$).

Subsequent t tests indicated that in the silent task condition, recollection was better for taboo words than negative words ($t(20)=5.20$, $p < .0001$), and marginally better for negative than neutral words ($t(20)=1.74$, $p < .1$). In the easy task condition, recollection was better for the taboo words than the negative words ($t(20)=4.64$, $p < .0001$), and similar for the negative and neutral words ($p > .8$). In the hard task condition, recollection was better for the taboo words than the negative words ($t(20)=7.87$, $p<.0001$), and did not differ for the negative and neutral words ($t(20)=1.59$, $p>.15$).

Familiarity did not differ between the taboo and negative words encoded with the silent task ($p>.5$) or easy task ($p>.4$), but familiarity was marginally greater for the taboo words encoded with the hard task ($t(20)=2,25$, $p<.05$). Familiarity was greater for the negative words than the neutral words with the silent task ($t(20)=3.09$, $p<.01$), and did not differ with the easy task ($p>.15$) or hard task ($p>.15$).

Effect of Secondary Task and Item Type on the Magnitude of the Enhancement Effect

We computed the enhancement effects for taboo items (e.g., "remember" responses to taboo items minus "remember" responses to neutral items) and the enhancement effects for negative items (e.g., "remember" responses to negative items minus "remember" responses to neutral items).

Repeated-measures ANOVA conducted on the overall enhancement effect (computed using corrected recognition scores) indicated no effect of task ($p>.3$), a significant effect of item ($F(1,20)=16.83$, $p<.01$), and a significant interaction between item type and task ($F(2,40)=7.42$, $p<.01$). Subsequent t tests confirmed that the enhancement effect for the taboo words was unaffected by the task manipulation ($p>.15$), whereas the enhancement effect for the negative words was reduced by the attention manipulation ($t(20)=3.02$, $p<.01$). This interaction between task and item type also existed when "remember" enhancement scores or recollection enhancement scores were analyzed; subsequent t tests indicated

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[11] In this scoring system, recollection and familiarity are scored along different scales;

that the recollection enhancement for taboo items marginally increased with the task manipulation (t(20)=1.91, p<.10), whereas there was no effect on the recollection enhancement for negative words (p>.7). Similarly, the "remember" enhancement increased across the attention conditions for the taboo words (t(20)=2.58, p<.05), but task had no effect for the negative words (p>.7).

Discussion

The critical findings of Experiment 1 were that the recollective enhancement for negative (valence-only) words, or the enhancement in the "remember" responses for these words, was eliminated by the divided attention manipulation. In contrast, the recollective enhancement remained for the arousing (taboo) words, even when attentional resources were diverted to a hard secondary task.

This dissociation suggests that distinct cognitive processes contribute to the ability to encode detailed information about words with only valence as compared to words with arousal. The memory benefit for the arousing words appears to be related to relatively automatic processes that are not disrupted by the divided attention manipulation. Thus, even when participants had to perform a difficult concurrent task, the recollective enhancement for the taboo words remained. Attention may be automatically oriented toward these stimuli, and they may be processed faster than the negative or neutral stimuli. The amygdala has been shown to be able to bias attention, or to permit prioritized computation of arousing stimuli (Vuilleumier et al., 2002; Vuilleumier et al., 2001; Vuilleumier & Schwartz, 2001; Whalen et al., 1998). It may also be able to bias

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therefore, the main effect of memory strength here and elsewhere is not surprising.

lower-level capacities, such as visual processing (Tabert et al., 2001; LeDoux, 1995), thereby allowing for more automatic analysis of arousing stimuli.

In contrast, the recollective enhancement for the valence-only words seemed to rely on controlled, attention-demanding processes. Individuals may semantically elaborate on the items, may cluster the items together, or may use autobiographical elaboration to improve their memory for these items. This increased elaboration could occur via limbic biasing of neural circuitry used for encoding. For example, the amygdala could bias the processing in prefrontal cortex regions thought to be important for source memory (Wegesin et al., 2002; Wilding, 1999; Ranganath et al., 2000; Johnson et al., 1997), or it could bias processing in other medial temporal-lobe regions important for feature binding or associative learning (Mitchell et al., 2000; Sperling et al., 2001; Yonelinas et al., 2001). It is also possible that the elaborative effect is unrelated to limbic interactions; it may be that words with valence have features that make them easier to elaborate. For example, these valenced words stimuli may be more personally relevant or interesting, and these features could contribute to the increased elaboration.

Most of these factors (e.g., personal relevance, level of interest) presumably are closely tied to emotion (i.e., personally relevant items tend to carry emotional significance not associated with non-personally relevant words), and thus are difficult to tease apart from the dimension of emotion. One dimension that can be controlled, however, is semantic relatedness. A potential explanation for increased elaboration to negative items is that negative words can all be thought of as semantic associates (i.e., "negative" can be thought of as a semantic category). It is, therefore, possible that memory for the negative words was better than for the neutral words because of this semantic clustering. To address this possibility, Experiment 2 asked whether the effect of divided attention would be the same if the neutral words were all semantic associates.

Experiment 2: Effects of Divided Attention on Memory for Arousing and Valenced Items: Effects of Semantic Clustering

Experiment 2 sought to replicate the critical findings of Experiment 1: specifically, the finding that memory for arousing words was resistant to the effects of divided attention, whereas memory for valenced, non-arousing words was not. In this experiment, we included the semantically associated neutral words, rather than the unrelated neutral items used in Experiment 1. This manipulation, therefore, controlled for effects of semantic clustering that might have contributed to enhanced memory for valenced and arousing words in Experiment 1.

Methods

Participants

The participants comprised 20 males, ages 19-32 years (mean = 24.2) with 14-18 years of education (mean = 14.6).

Design and Materials

The materials and design were identical to that of Experiment 1, with the exception that all neutral words were associates of the words "think" or "mind."

Table 2. Experiment 2: Memory performance as a function of item and task type (mean, SD).

		Corrected Recognition			
Task	**Item Type**	**Remember**	**Know**	**Recollection**	**Familiarity**
None	Taboo	.69 (.15)	.00 (.12)	.75 (.17)	2.2 (1.1)
	Negative	.61 (.17)	.09 (.14)	.67 (.18)	2.1 (1.1)
	Neutral (Semantic Assoc)	.54 (.21	.07 (.19)	.59 (.21)	1.5 (1.1)
Easy	Taboo	.71 (.10)	.03 (.08)	.77 (.11)	2.3 (1.0)
	Negative	.50 (.22)	.06 (.13)	.55 (.23)	1.3 (0.9)
	Neutral (Semantic Assoc)	.54 (.21)	.07 (.15)	.60 (.25)	1.5 (0.7)
Hard	Taboo	.68 (.14)	.02 (.10)	.74 (.15)	1.8 (1.2)
	Negative	.48 (.19)	.08 (.16)	.53 (.21)	1.1 (0.8)
	Neutral (Semantic Assoc)	.41 (.20)	.13 (.13)	.46 (.21)	1.4 (1.0)

Results

Overall Correct Recognition (Collapsing across Remember and Know Responses)

Repeated-measures ANOVA indicated a significant effect of item type (F(2,38)=18.34, p<.0001) and task (F(2,38)=12.14, p<.0001), and a significant interaction between item type and task (F(4,76)=8.04, p<.0001) (Table 2).

Subsequent t tests indicated that participants' memory was similar for taboo and negative words encoded with the silent task (p>.4), and that memory for both of these word types was better than memory for neutral words encoded with the silent task (t(19)>2.0, p<.05). When words were encoded with the easy auditory distracter task, memory was better for the taboo words than for the negative words (t(19)=4.07, p<.001), and did not differ between the negative and neutral words (p>.1). When words were encoded with the hard auditory distracter task, memory was better for the taboo words than the negative words ($t(19)=7.13$, $p<.0001$), but did not differ for the negative and neutral words ($p>.5$).

Remember and Know Responses

Repeated-measures ANOVA indicated a significant effect of item type ($F(2,38)=17.95$, $p<.0001$), task ($F(2,38)=12.69$, $p<.0001$), memory strength ($F(1,19)=101.93$, $p<.0001$), interaction between item type and task ($F(4, 76)=7.94$, $p<.0001$), item type and memory strength ($F(2, 38)=33.81$, $p<.0001$), task and memory strength ($F(2,38)=4.15$, $p<.05$), and no three-way interaction.

Subsequent t tests indicated that participants gave an increased number of "remember" responses to taboo words as compared to negative words encoded with the silent task ($t(19)=2.11$, $p<.05$), the easy task ($t(19)=5.06$, $p<.0001$), or the hard task ($t(19)=6.60$, $p<.0001$), and an increased number "remember" responses to negative as compared to neutral words encoded with the silent task ($t(19)=2.52$, $p<.05$). "Remember" responses for negative and neutral items did not differ in the easy and hard task conditions.

Participants' "know" responses were greater for the neutral words than for the taboo words or negative words encoded with the silent task ($t(19)>3$, $p<.01$), and were greater for neutral than taboo words encoded with the hard task ($t(19)=4.01$, $p<.001$). No other comparisons were significant (all $p>.15$).

Recollection and Familiarity

Repeated-measures ANOVA indicated a significant effect of item type ($F(2,38)=13.84$, $p<.0001$), task ($F(2,38)=7.90$, $p<.001$), and memory type ($F(1,19)=47.94$, $p<.0001$), an interaction between item type and task ($F(4,76)=2.68$,

$p<.05$), item type and memory type ($F(2,38)=4.05$, $p<.05$), task and memory type ($F(2,38)=3.62$, $p<.05$), and a marginal three-way interaction between item type, task, and memory type ($F(4,76)=2.37$, $p<.06$).

Subsequent t tests indicated that recollection was greater for the taboo words than the negative words encoded with no secondary task ($t(19)=2.22$, $p<.05$), the easy task ($t(19)=5.10$, $p<.0001$), or the hard task ($t(19)=6.42$, $p<.0001$). Recollection was greater for the negative than neutral words when encoded with no secondary task ($t(19)=2.71$, $p<.01$), but not when encoded with the easy or the hard task ($p>.15$).

Familiarity did not differ between the taboo and negative words encoded with no secondary task ($p>.8$), but familiarity was greater for the taboo words encoded with the easy task ($t(19)=4.00$, $p<.001$), or the hard task ($t(19)=2.62$, $p<.05$). Familiarity was greater for the negative than the neutral words encoded with no secondary task ($t(19)=3.22$, $p<.01$), but not with the easy or hard task ($p>.15$).

Effect of Secondary Task and Item Type on Magnitude of the Enhancement Effect

We computed the enhancement effect for taboo items (e.g., "remember" responses to taboo items minus "remember" responses to neutral items) and the enhancement effect for negative items (e.g., "remember" responses to negative items minus "remember" responses to neutral items).

Repeated-measures ANOVA conducted on the overall enhancement effect (computed using corrected recognition scores) indicated no effect of task ($p>.4$), a significant effect of item ($F(1,19)=17.22$, $p<.01$), and a significant interaction between item type and task ($F(2,38)=17.56$, $p<.0001$). Subsequent t tests indicated that the enhancement effect for the taboo words was marginally increased by the task manipulation ($\underline{t}(19)=1.83$, $\underline{p}<.09$), whereas the enhancement effect for the negative words was significantly reduced by the attention manipulation ($\underline{t}(19)=2.10$, $\underline{p}<.05$). This interaction between task and item type also existed when "remember" enhancement scores or recollection enhancement scores were analyzed.

Subsequent $\underline{t}$ tests indicated that the recollection enhancement for taboo items increased marginally with the task manipulation ($t(19)=1.77$, $p<.10$), whereas there was no effect on the recollection enhancement for negative words ($p>.9$). Similarly, the "remember" enhancement increased marginally across the attention conditions for the taboo words ($t(19)=2.01$, $\underline{p}<.06$), but not for the negative words ($\underline{p}>.9$).

Discussion

Experiment 2[12] replicated the critical findings of Experiment 1: The recollective enhancement for the taboo words was unaffected by divided attention, whereas the recollective enhancement for the negative words was eliminated when participants were required to perform the secondary task. The divergence of the effects of divided attention on the enhancement effect for the arousing words versus the valence-only words suggests that memory for arousing words is enhanced due to relatively automatic processes, whereas the enhancement for valenced items is more reliant on attention-demanding

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[12] This pattern of results was also replicated when words were presented in blocks (e.g., all arousing, all neutral, etc).

processes. These attention-demanding processes for the negative items do not appear to be related only to semantic clustering: The enhancement for the negative items in the no-task condition remained even when the neutral words were semantic associates. Thus, the elaborative benefit for the negative words was not just related to their ability to be categorically clustered.

General Discussion

The main question motivating this set of experiments was whether controlled or automatic processes led to the recollective memory enhancement for negative stimuli. The answer apparently depends on whether the stimuli differ in arousal or in valence. Memory enhancement effects were found for stimuli that differed from neutral stimuli only in valence, as well as for stimuli that differed in arousal. The processes contributing to these enhancement effects, however, were dissociable. In particular, memory for the arousing items was enhanced based on relatively automatic processes that were unaffected by attention modulation. Thus, memory for the taboo words was not reduced when individuals were asked to carry out a hard secondary task. Limbic regions, including the amygdala, likely allow for a rapid processing of the arousing nature of stimuli; when stimuli are deemed as arousing or threatening, these limbic regions may be capable of biasing lower-level processes to allow for prioritized processing of emotional stimuli (Vuilleumier et al., 2001; Vuilleumier et al., 2002; Whalen et al., 1998). These types of automatic processes, such as biasing or attention or prioritized processing, appear to contribute to our enhanced memories for arousing words.

In contrast, when words differ in valence only (i.e., not in arousal), the same types of automatic processes may not occur. Instead, controlled attention-demanding processes appear to underlie the memory benefit for these types of stimuli. Thus, the recollective memory enhancement for items with valence was eliminated when encoding resources were taxed by a concurrent secondary task. It is still unclear exactly what these controlled processes may be. They may be elaborative processes specific to emotional stimuli, or, perhaps more likely, they reflect processes (e.g., rehearsal, semantic and autobiographical elaboration) carried out with neutral stimuli, but that are more likely to occur during the encoding of emotional stimuli.

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Chapter 4

Two Routes to Emotional Memory: Distinct Neural Processes Support Memory Formation for Emotional Information with and without Arousal

Emotional information is better remembered than neutral information. We conducted fMRI and behavioral studies to ascertain whether emotional memory enhancement is monolithic or due to distinguishable components. We found that two distinct processes contribute to emotional memory enhancement, depending on whether the emotional information is arousing or nonarousing (valence-only). Successful memory formation for valence-only and neutral words depended on a prefrontal-hippocampal network implicated in self-initiated, controlled encoding processes (e.g., elaboration). In contrast, successful memory formation for arousing words depended on an amygdalar-hippocampal network. A behavioral companion study, employing a divided attention paradigm, confirmed that memory enhancement for valence-only words relied on controlled processes: Concurrent task performance reduced the enhancement effect. The enhancement for arousing words occurred more automatically, even when encoding resources were diverted to the secondary task.

An abundance of anecdotal and empirical evidence indicates that information with emotional salience is better remembered than information lacking emotional import (see Dolan, 2002; Hamann, 2001 for reviews). The amygdala is critical for this effect: Patients with amygdalar lesions show a blunted enhancement effect (Adolphs, Cahill, Schul, & Babinsky, 1997; Phelps, LaBar, & Spencer, 1997; Cahill, Babinksy, Markowitsch, & McGaugh, 1995), and neuroimaging studies reveal a relation between the amount of amygdalar activation at encoding and the likelihood of later retrieving emotional information (Hamann, Ely, Grafton, & Kilts, 1999; Cahill et al., 1996; Canli et al., 1999; Dolcos et al., in press; Cahill et al., 2002). Although the specific role of the amygdala in memory was debated for decades (Scoville & Milner, 1957; Weiskrantz, & Warrington, 1956; Zola-Morgan et al., 1989), recent evidence suggests that this structure exerts its role in emotional memory via modulation of hippocampal function (see McGaugh et al., 1992, and McGaugh, 2000, for reviews). While ample evidence supporting this hypothesis has been uncovered in animals (see McGaugh et al., 1992), to our knowledge, no neuroimaging evidence exists showing a link between amygdalar and hippocampal activation in humans. The first goal of the present study was, therefore, to examine the relation between amygdalar and hippocampal activation while individuals learned arousing words.

Although the evidence implicating the amygdala in emotional memory is strong, further specification of the cognitive and neural processes is needed. Various cognitive processes could contribute to the memory enhancement effect. Some may be self-generated, controlled processes: Individuals may be more likely to elaborate on emotional information (semantically or autobiographically) or to rehearse emotional information (see Christianson & Engelberg, 1999, for review). For example, presentation of emotional items (e.g., cemetery) may be more likely to remind an individual of a personal event than neutral items (e.g., cabbage), and thus, individuals may be more likely to associate emotional items with personal experiences. Other processes may be relatively automatic: Attention may be directed toward threatening or aversive stimuli (Pratto & John, 1991; Williams, Mathews, & MacLeod, 1996; Whalen et al., 1998; but see Pessoa et al., 2002), and these stimuli may benefit from prioritized or facilitated processing (Anderson & Phelps, 2001; Morris et al., 1998; Vuilleumier et al., 2002). Different neural substrates may underlie the controlled versus automatic processes that contribute to the enhancement effect. Prefrontal cortex has been implicated in controlled processes like elaboration or rehearsal, such that items which evoke prefrontal activation (and, thus, the additional use of such strategies) are more likely to be remembered than items that engage prefrontal cortex to a lesser extent (see Gabrieli et al., 1998; Paller & Wagner, 2000; Fernandez & Tendolkar, 2001; Fletcher, Shallice, & Dolan, 1997 for reviews). In contrast, automatic capture of attention by emotion is likely mediated by the amygdala (Anderson & Phelps, 2001), perhaps via its connections to lower-level sensory areas (Tabert et al., 2001; LeDoux, 1995).

The types of processes engaged may also differ depending on the particular stimulus characteristics. Emotional information is thought to be characterized in two dimensions: Arousal (how exciting or calming) and valence (how positive or negative) (e.g., Russell, 1980; Bradley, Greenwald, Petry, & Lang, 1992). Evidence suggests that the amygdala's role in emotional memory is related to arousal. Pharmacological manipulations that increase arousal levels (e.g., administration of adrenergic agonists) enhance memory performance in animals and humans, while the memory facilitation typically associated with emotional arousal is eliminated by administration of a beta-adrenergic antagonist (see McGaugh et al., 1992; McGaugh, 2000; Buchanan & Adolphs, in press, for reviews).

The majority of studies examining the effect of emotional content on long-term memory have used arousing stimuli; however, items that are not arousing but have valence (and, in particular, that participants judge to be "negative") are also better remembered than neutral stimuli (e.g., Ochsner, 2000; Kensinger et al., 2002). The neural processes contributing to this enhancement effect have not been examined. Prior neuroimaging studies investigating the neural processes that underlie the ability to learn emotional information have used stimuli that contain both valence and arousal (i.e., that are negative and arousing - Canli et al., 2000; Tabert et al., 2001; Cahill et al., 2001 - or, less frequently, positive and arousing - Dolcos et al., in press; Dolcos & Cabeza, 2002; Hamann et al., 1999). Thus, the second goal of the present study was to show whether the processes that contribute to successful memory formation for arousing items also support successful encoding of items with valence only, or whether distinct processes underlie the memory benefit for items with valence only. Based on the studies linking amygdalar modulation of memory to arousal (see Cahill & McGaugh, 1998; Hamann, 2001; LaBar & Phelps, 1998), it was probable that the memory benefit for negative words lacking in arousal (valence-only words) would be mediated by non-amygdalar processes. We hypothesized that this valence-only memory benefit would, instead, be mediated via the effect of emotion on controlled, encoding processes, such as deeper elaborative processing, and that prefrontal cortex would be recruited for this purpose.

Methods

Participants provided informed consent in a manner approved by the MIT and MGH Institutional Review Boards; they were remunerated at $25/hour for their participation. Participants comprised 28 young adults (14 women) who were scanned on a Siemens (Erlangen, Germany) Allegra 3 Tesla head-only MRI scanner while they encoded words that were completely neutral, negative and nonarousing (e.g., sorrow, mourning), or negative and arousing (e.g., rape, slaughter). Words were presented for 2 sec each, pseudorandomly intermixed with fixation crosses to provide jitter (Dale, 1999; Burock et al., 1998); participants rated each word as "abstract" or "concrete."

Each encoding scan was followed by a retrieval task (after approximately a 10-min delay), in which participants indicated whether they (a) vividly remembered seeing the word at encoding (i.e., remembered something specific about the item's presentation, such as something they thought of when they saw the word), (b) sensed that the word was familiar and thus thought it had been presented at study, but did not remember any details about its prior presentation (see Yonelinas, 2002, for review of this distinction), or (c) believed the word had not been presented at study. After all encoding and retrieval sessions were completed, participants rated the words for valence (i.e., how positive and negative) and arousal (i.e., how calming or exciting), each on a scale from 1-7. These ratings were used to place words into three categories: (a) negative (valence of 1-2) and nonarousing (arousal of 1-4), (b) negative (valence of 1-2) and arousing (arousal of 5-7), and (c) neutral (valence of 3-5, arousal of 1-4). On average, 123 words (SD=24.8) were rated by participants as neutral words, 90 (SD=28.8) as negative and nonarousing, and 85 (SD=46.5) as negative and arousing.

Data Analysis

The data were preprocessed using SPM99 (Wellcome Department of Cognitive Neurology, London). Images were corrected for slice timing and rigid body motion. Functional data were then spatially normalized to the Montreal Neurological Institute template. Images were resampled into 3 mm cubic voxels and smoothed spatially with an 8 mm full-width half-max isotropic Gaussian kernel.

Statistical analyses were performed using the general linear model in SPM99. Trials from each condition were modeled using a canonical hemodynamic response function. Effects for each condition were estimated using a subject-specific, fixed-effects model. These data were then entered into a second-order, random-effects analysis. To assess the effect of encoding, the experimental trials at encoding (collapsing across item type) were contrasted to the baseline (Fixation). Activation was considered reliable if the area included at least 5 voxels at $p < 0.001$ uncorrected. The encoding-related regions of interest (ROIs) were defined from this contrast. These regions were unbiased with respect to the item type and allowed a way to assess the effect of emotion and subsequent memory (i.e., activation related to whether an item was remembered or forgotten) in regions associated with episodic encoding. ROIs were 8mm spheres, with the exception of the amygdala; because the amygdala is a punctate region, a 3mm sphere was used to define the amygdalar ROI.

Results

Behavioral data

An ANOVA indicated a significant effect of emotion type (arousing, valence-only, neutral) and response type (remember, know), and an interaction between emotion type and response type (all $p < 0.01$). Subsequent t tests indicated that participants remembered more negative, arousing words (87%) and negative, nonarousing words (85%) than neutral words (77%). The majority of correct responses were "remember" responses (69% for negative, arousing; 67% for negative, nonarousing, and 54% for neutral); the "know" responses did not differ across the three emotional categories.

Neuroimaging data: Encoding

We conducted a random-effects, voxel-based analysis to compare brain activity during all encoding trials, collapsing across word types, as compared to fixation (Table 1). This contrast was then used to define ROIs. For each ROI, we examined the peak percentage signal change that occurred 2-6 sec following stimulus onset. An ANOVA was conducted on these signal change values to examine the effects of emotion type (negative arousing, negative nonarousing, neutral) and subsequent memory (remembered, forgotten).

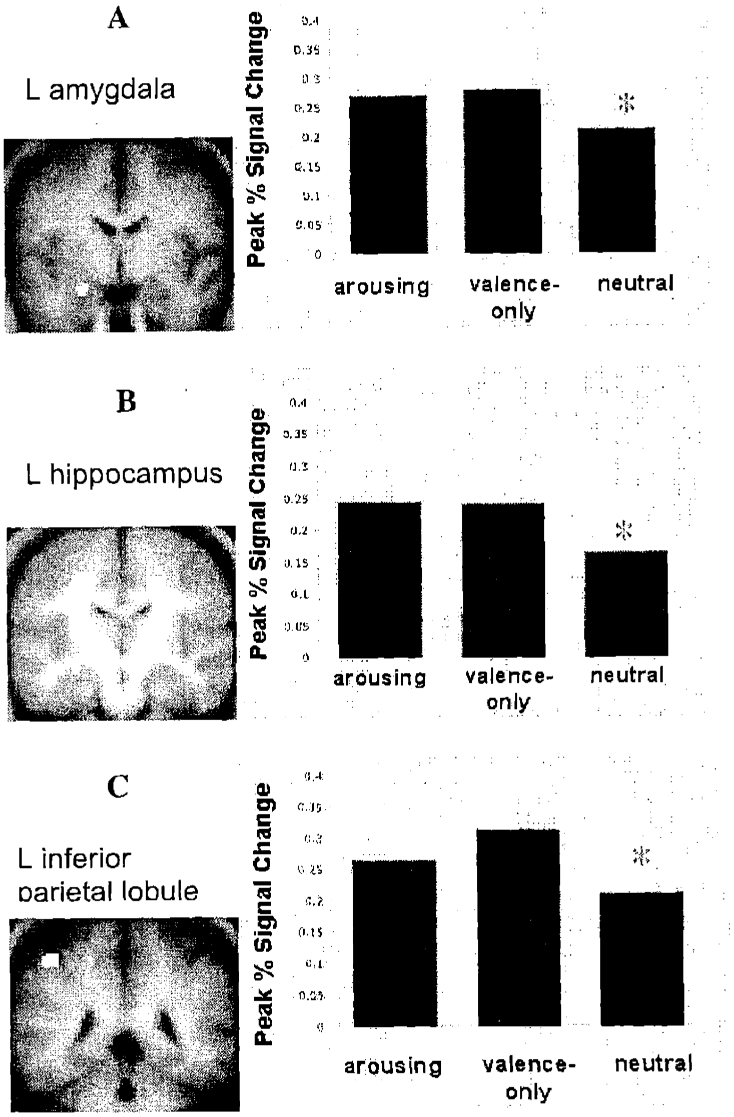
Table 1. Regions activated during encoding (at least 5 voxels, $p < 0.001$ uncorrected)

Brain region	Hemisphere	Talairach coordinates (x, y, z)	Brodmann area
Occipital lobe	L	-21, -102, 0	17, 18
	R	27, -99, -3	
	R	33, -93, -6	
Inferior parietal lobule	L	-48, -42, 54	40
	R	54, -33, 51	40
Inferior prefrontal gyrus	L	-54, 24, -9	47
	L	-51, 36, 15	45, 46
	L	-51, 18, 30	9, 44
	R	48, 24, -15	47
Dorsolateral PFC	L	-48, 33, 27	9, 46
	R	48, 42, 15	9, 46
Superior prefrontal gyrus	L	-3, 27, 42	8
	L	-6, 18, 66	6
	L	-30, 9, 60	6
	R	0, 18, 51	8
Uncal hippocampus	R	27,6,-18	
Anterior hippocampus	L	-30, -15, -12	
Amygdala	L	-27, -3, -12	
	R	27, 0, -18	
Claustrum	R	30, 3, -6	
Basal ganglia	L	-24, -6, 6	

Neuroimaging data: Emotion Effect

In the left hemisphere, the hippocampus, amygdala, and inferior parietal lobule (Brodmann Area, BA 40) showed a greater response to emotional arousing and emotional nonarousing words than to neutral words (Figure 1). Thus, these regions were modulated by the presence of any emotional salience (valence or arousal).

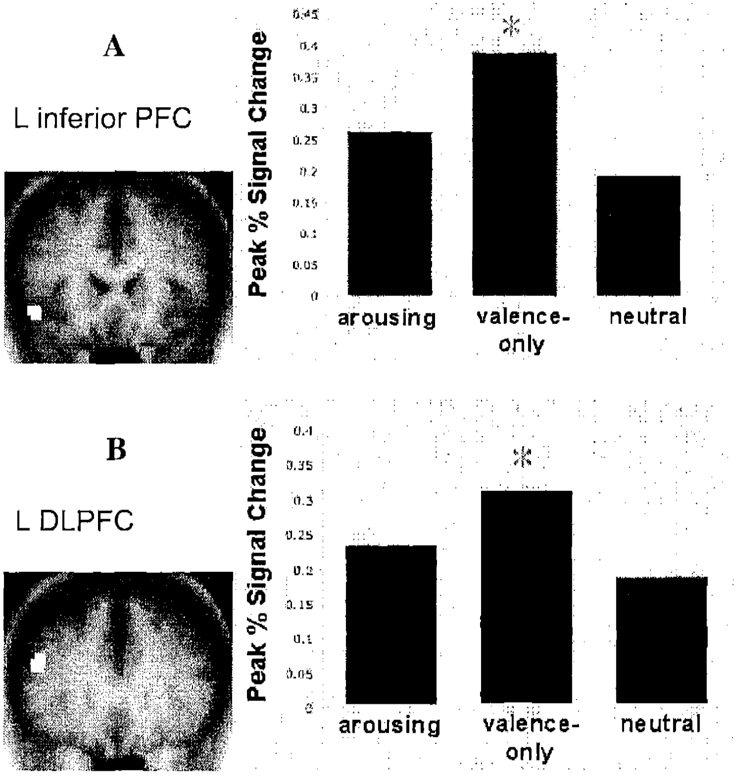
Figure 1. Activation in the left amygdala (A), left anterior hippocampus (B), and bilateral inferior parietal lobule (C) was greater during the encoding of emotional words (with or without arousal) than neutral words.



The inferior parietal lobule has been implicated in processing of verbal information related to the self (Kircher et al., 2000), attention (see Culham & Kanwisher, 2001, for review), and working memory processing of emotional content (Rama et al., 2001). Any of these possibilities could explain the recruitment of inferior parietal lobule for processing emotional categories of words. The modulation of the amygdala to the valence-only words suggests that, with verbal stimuli at least, the amygdala may not be selectively modulated by arousal. In the present study, the amygdala showed above-baseline activation even for the neutral words. It has been proposed that the amygdala may be engaged during the processing of ambiguous stimuli (Hamann et al., 2002; Whalen, 1998); the amygdala may, therefore, have been engaged during the processing of all of the words as the verbal stimuli all had to be processed to some level before their threat (or lack thereof) could be evaluated.

In contrast to the regions that were modulated by any emotional salience (arousing or valence-only words), the left inferior prefrontal cortex (PFC; BA 47) and left dorsolateral PFC (BA 9 and 46) showed greater activation during encoding of emotional, nonarousing words (Figure 2). The activation in the left PFC may reflect additional, self-initiated encoding processes that were carried out on the valence-only words, such as autobiographical or semantic elaboration, or additional rehearsal. This explanation would be consistent with prior studies implicating these PFC regions with elaborative encoding processes (see Fernandez & Tendolkar, 2001; Fletcher et al., 1997; Gabrieli et al., 1998 for reviews).

Figure 2. Activation in the left inferior (A; BA 47) and dorsolateral (B; BA 9/46) PFC was greater during the encoding of valence-only words, as compared to arousing words or neutral words.



Neuroimaging Data: Subsequent Memory Effect

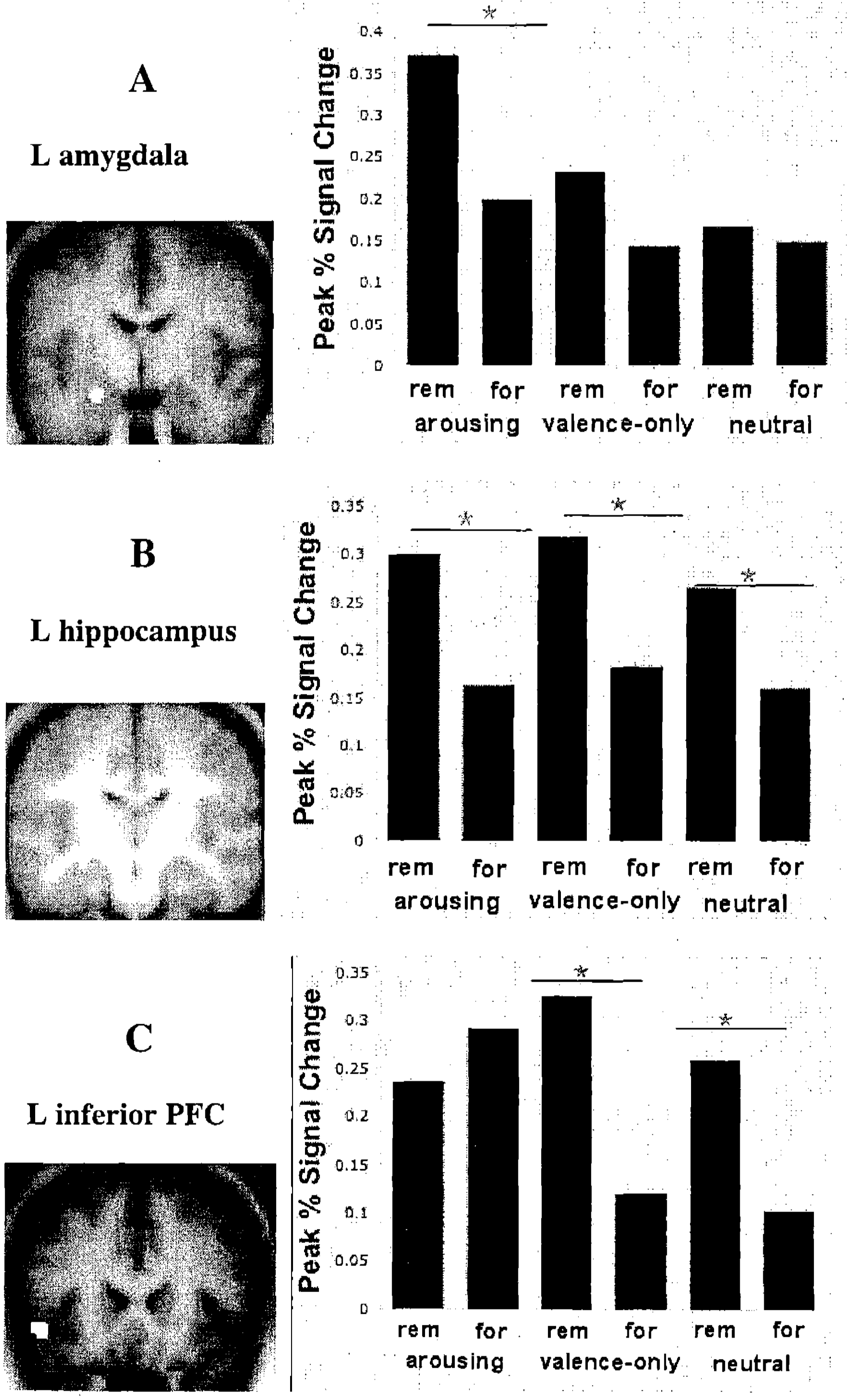
To gain leverage on whether distinct neural processes contributed to the successful encoding of arousing words versus nonarousing words, encoding-related brain activity in the defined ROIs was compared for words that were later vividly remembered by the participant as compared to words that were later forgotten (i.e., participants later incorrectly indicated that the word had not been previously studied). Because accuracy for the arousing words was very high, the subsequent memory analyses are shown for the 19 individuals (9 women) who had a sufficient number of forgotten, arousing words (at least 12) to permit the subsequent memory analysis. The results for the valence-only and neutral words remained qualitatively the same when the data from all 28 participants were analyzed.

This subsequent memory analysis revealed distinct networks supporting memory formation for arousing words versus nonarousing words. Activation in the left amygdala and left hippocampus correlated with successful memory formation for the arousing words (Figure 3). Further, the activation in these regions during the encoding of subsequently remembered, arousing words was correlated (Figure 4).

In contrast, activation in the left inferior PFC and left hippocampus related to successful memory formation for the valence-only words and the neutral words (Figure 3). An ANOVA with region, emotion type, and subsequent memory as factors indicated a significant interaction between item type and subsequent memory ($\underline{p}<.01$): Activation in these regions was stronger for subsequently remembered valence-only words than for subsequently remembered neutral words, whereas the activation to forgotten valence-only and forgotten neutral words did not differ.

These results suggest that distinct processes contribute to memory formation for arousing words versus words without arousal. Specifically, amygdalar activation appears to correlate with subsequent memory performance only when the items are arousing. This result is consistent with prior studies in which amygdalar activation related to successful memory formation only for items that participants rated as highly emotional (Cahill et al., 1999). Further, for subsequently remembered arousing words, activation in the amygdala and hippocampus was correlated, consistent with the hypothesis that amygdalar activity modulates hippocampal function. Thus, to our knowledge, this study

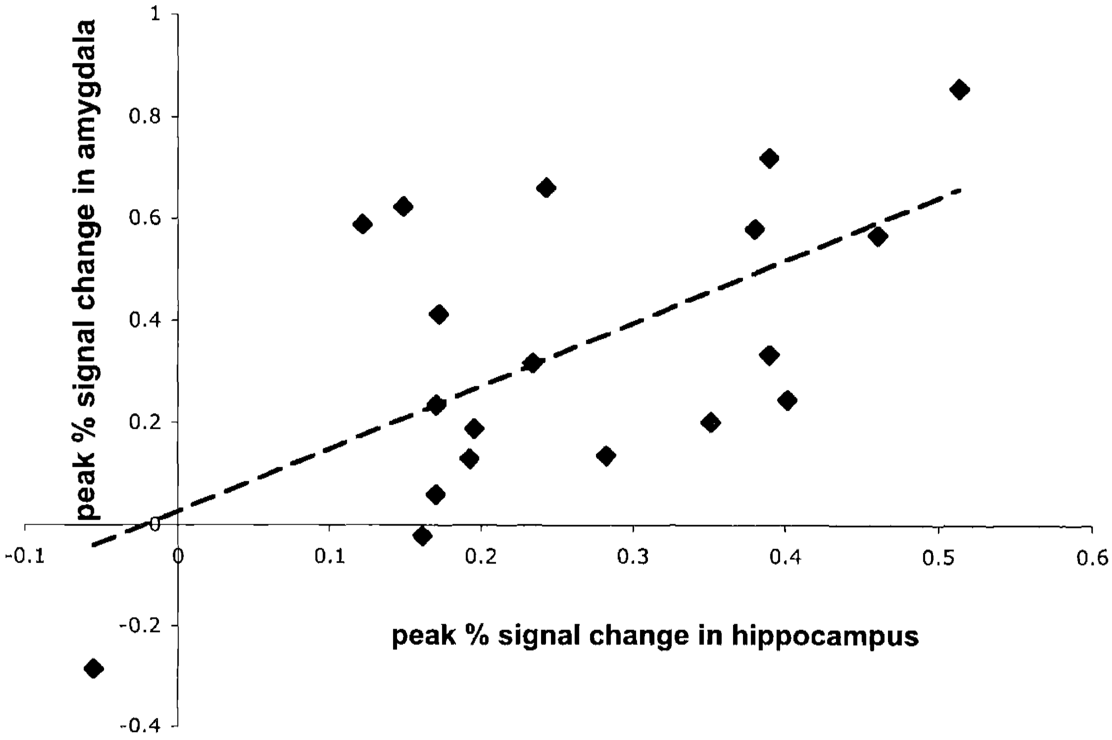
Figure 3. Activation in the left amygdala (A) and left anterior hippocampus (B) related to subsequent memory for the arousing words, whereas activation in the left hippocampus (B) and left inferior PFC (C) were associated with subsequent memory for the valence-only words, and the neutral words. The relation between subsequent memory and activation in the left hippocampus and left inferior PFC was greater for the valence-only words as compared to the neutral words ($p < 0.01$). While activation in these regions was similar for forgotten (for) valence-only words and forgotten neutral words, activation was greater for remembered (rem) valence-only words as compared to remembered neutral words.



provides the first evidence in humans of a connection between amygdalar and hippocampal activation during the encoding of arousing words.

In contrast to the amygdalar-hippocampal network recruited for encoding of arousing words, left inferior PFC activation supported successful memory formation for valence-only words, as well as for words that were neutral, but not for arousing words. The fact that activation in this region was greater during the successful encoding of valence-only words as compared to neutral words suggests that valence-only items show memory benefits due to additional engagement of these types of controlled processes (e.g., elaboration).

Figure 4. For arousing words that were later remembered, the activation in the hippocampus and the amygdala was correlated ($r = 0.60$, $p < 0.01$; dotted line represents linear trendline).



Behavioral Companion Study

The subsequent memory analyses were consistent with the hypothesis that amygdalar modulation of hippocampal function underlies the memory benefit for arousing words (see McGaugh, 2000 for review). Amygdalar activation to threatening or aversive stimuli is believed to occur relatively automatically, and even when attentional resources are taxed (Vuilleumier et al., 2001; Whalen et al., 1998). Thus, amygdalar modulation of hippocampal function could occur relatively automatically. In contrast, the neuroimaging data suggest that the processes associated with the enhancement for the valence-only items are attention-demanding, controlled processes.

To examine whether this interpretation was supported, we employed a divided attention paradigm to address whether additional encoding resources were required for the enhancement for the valence-only words versus the arousing words. In the divided attention paradigm, participants are required to perform a concurrent task as they encode words. By varying the difficulty of this concurrent task, the resources that can be devoted toward encoding are modulated (e.g., Naveh-Benjamin et al., 2000; Craik et al., 1996). This divided attention manipulation has been shown to have a greater impact on controlled encoding processes, and a lesser effect on relatively automatic information processing (see Yonelinas, 2002, for review). Thus, if self-generated, controlled encoding processes were responsible for the enhancement effect for valence-only items, but were less important for the enhancement for arousing items, the enhancement for the valence-only items should be disproportionately reduced by the divided attention manipulation.

To investigate whether this hypothesis would be upheld, 24 participants (12 women) encoded words used in the fMRI experiment while (a) performing a hard auditory discrimination task, (b) performing an easy auditory discrimination task, or (c) performing no secondary task (see Kensinger et al., in press, for details of the auditory discrimination task). The results supported the hypothesis that encoding of valence-only words disproportionately recruited self-generated encoding processes: When individuals performed a concurrent task, the memory enhancement for the valence-only words disappeared, whereas the memory enhancement for the arousing words remained (Table 2).

Table 2. Behavioral companion study: Mean percentage correct (SE) as a function of item type (arousing, valence-only, neutral) and attention condition at encoding (no, easy, or hard secondary task).

	No Task	Easy Task	Hard Task
Arousing	88 (3)	84 (3)	83 (3)
Valence only	83 (3)	71 (3)	62 (3)
Neutral	75 (3)	68 (3)	60 (3)

Discussion

Two main conclusions emerge from the present study. First, to our knowledge, this study provides the first direct evidence in humans of a link between amygdalar activation, hippocampal activation, and subsequent memory. During successful encoding of arousing words, the activation in these regions was correlated. This correlation is consistent with the hypothesis (see McGaugh, 1992) that activation in the amygdala results in modulation of hippocampal function (although the correlation cannot provide evidence of the direction of modulation, i.e., amygdalar-hippocampal or hippocampal-amygdalar). The fact that this relation occurred only for arousing words is also consistent with the modulation hypothesis. Although the details of the modulatory effect are still being discussed, they likely result from interactions with stress hormones – epinephrine and corticosteroids – which are released as part of the response to emotionally arousing events (McGaugh, 2000). The results of our study further suggest that this modulation occurs even when attentional resources are taxed; thus, even when encoding resources were devoted toward a secondary task, the memory enhancement for arousing words remained. This result corroborates evidence suggesting that amygdalar activation to emotional stimuli can occur even when attentional resources are taxed, and possibly in the absence of attention (Vuilleumier et al., 2001; Whalen et al., 1998).

Second, this study indicates that although arousing words and valence-only words are, at least in some instances, more likely to be remembered than neutral words, distinct cognitive and neural processes contribute to these enhancement effects. Valence-only words are enhanced due to additional recruitment of the same types of self-generated, controlled, processes as are used to encode neutral words. Individuals may be more likely to elaborate on, or to rehearse, these valence-only words as compared to neutral words. This hypothesis is supported by the neuroimaging data: Activation in regions associated with controlled encoding processes (e.g., PFC) was greater for valence-only words than for neutral words, and the relation between activation and subsequent memory in these regions was stronger for valence-only words than for neutral words. The results from the divided attention behavioral companion study also supported this hypothesis: Diversion of resources from the encoding task eliminated the memory enhancement for the valence-only words, presumably by reducing the participants' ability to engage in these additional, controlled, processes.

In summary, there appear to be distinct mechanisms that support memory enhancement for emotional information, depending on whether that information is arousing or contains only valence. The enhancement for valence-only items is supported by a PFC-hippocampal network that has been implicated in memory formation for neutral information, and is associated with controlled, self-generated encoding processes, such as elaboration or rehearsal of information. In contrast, the memory enhancement for arousing items is mediated by an amygdalar-hippocampal network, which may reflect relatively automatic effects of emotion on memory, and may be specifically engaged when emotional stimuli elicit an arousal effect.

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Conclusion

The studies reported in this dissertation were conducted to examine the cognitive and neural processes that support our ability to richly remember neutral and negative words. Through use of a divided attention paradigm, the fMRI study in **Chapter 1** isolated brain regions associated with formation of vivid, detailed memories (formed when resources were primarily directed toward encoding) and less detailed, familiarity-based memories (formed in all encoding conditions). The results suggested that the neural processes supporting successful encoding of neutral words differed depending on the resources devoted toward encoding: Left prefrontal cortex and the left anterior hippocampus related to successful memory formation only when words were encoded with relatively full attention (when rich memories could be formed), whereas right prefrontal cortex and the left parahippocampal gyrus continued to support successful memory formation even when resources were diverted from the encoding task, and thus, primarily familiarity-based memories could be established.

The results of Chapter 1 converge with recent evidence (e.g., Davachi & Wagner, 2002; Davachi, Mitchell, & Wagner, 2003; Dobbins et al., 2002; Henson et al., 1999) indicating that, for neutral information, the ability to form or retrieve vivid, detailed memories can be dissociated from the ability to form or retrieve less vivid, familiarity-based memories.

No prior studies had extended these investigations to include information with emotional salience, despite an abundance of evidence suggesting that emotionally significant information is often vividly remembered (e.g., "flashbulb memories"; Brown & Kulick, 1977). **Chapter 2** confirmed that there is a qualitative enhancement for emotional words, such that items with valence or arousal are more likely to be vividly remembered than are neutral words. The effect was consistent across a series of studies analyzing subjective assessments of a memory's richness (using the "remember" – "know" distinction) as well as objective measures (source memory) assessing memory for contextual details present at study. The effect was remarkably consistent across participants, and was consistently stronger for words with arousal than for those with valence only.

The results of Chapter 2 extended understanding of the effect of emotion on memory by indicating that emotion not only enhances the likelihood of retrieving emotional information, but also the quality of the information retrieved. While the effect existed for items with valence only, as well as for items with arousal, the studies in Chapter 2 could not elucidate whether the processes contributing to those effects were similar or distinct. Many of the models of emotion's effect of memory have proposed that it is, specifically, the arousing effects of emotion that allow for memory modulation (e.g., McGaugh, 2000; Cahill & McGaugh, 1995). Thus, although the studies in Chapter 2 indicated a qualitative enhancement for words with valence only, and prior studies had demonstrated a quantitative enhancement (Ochsner, 2000; Kensinger et al., 2002), the possibility remained that distinct cognitive and neural processes were supporting the memory enhancement effects for items with valence only versus for items with arousal.

The studies reported in **Chapter 3**, therefore, utilized a divided attention paradigm to investigate the contributions of controlled, attention-demanding processes versus automatic processing to the qualitative enhancement for the words with valence only or with arousal. The results demonstrated a dissociation in the cognitive processes supporting the effects: Memory for the arousing words remained more detailed than memory for the other categories, even when resources were devoted away from the encoding task and toward the distractor task. In contrast, memory for the words with valence only appeared to rely more on controlled processes; thus, when resources were diverted from the encoding task, memory was no longer more detailed for the words with valence only than for the neutral words.

The fMRI study reported in **Chapter 4** extended these results by probing the neural processes contributing to the encoding of neutral words, words with valence only, and words with arousal. Dissociable neural networks supported the successful encoding of the two types of emotional words. The successful encoding of words with valence only was related to activation in a left prefrontal-hippocampal network that was also implicated in the successful encoding of neutral words (see also Chapter 1). The activation in the network, however, was greater during successful encoding of words with valence only as compared to neutral words. Thus, the enhanced richness of memories surrounding items with valence only appears to be due to modulation of the same processes that are important for the encoding of neutral words. Coupled with the results of Chapter 3, it appears that controlled, attentional processes (e.g., elaboration and rehearsal) underlie the increased detail encoded for words with valence only.

In contrast, successful encoding of arousing words was associated with activation in a distinct amygdalar-hippocampal network. This network has been implicated previously in memory for emotional information, in both animals (e.g., McGaugh, 2000) and humans (e.g., Dolcos et al., in press). Critically, these studies all had used arousing stimuli, and in fact, many of the studies found a relation between amygdalar activation and subsequent memory only for the items rated as most highly emotional (i.e., for those items with arousal; Canli et al., 2000). The results of this Chapter 4 are consistent with the results of these prior studies, indicating that the amygdala is only related to successful encoding for items that have arousal: The amygdala may require an above-threshold amount of arousal before it begins to modulate the function of other limbic structures (e.g., the hippocampus).

The results of Chapter 4 extend the results of prior investigations by indicating that the amygdalar-hippocampal network is not only related to the increased likelihood of remembering emotional information, but also to the increased detail included in the memories for the emotional information. Given recent evidence that the hippocampus plays a specific role in the formation of vivid, detailed memories as compared to familiarity-based memories (Davachi & Wagner, 2002; Davachi et al., 2003; see also Chapter 1), this ability for the amygdalar-hippocampal network to subserve the qualitative enhancement of emotional information is logical. Coupled with the results of Chapter 3, it appears that this amygdalar modulation occurs relatively automatically, such that the recollective memory benefit for arousing information can remain even in when controlled processes are minimized by the presence of a distractor task.

Future Directions

The results of the studies reported in this dissertation raise a number of questions that require further investigation. Below I briefly outline some of the questions that will need to be pursued to enhance understanding of the processes contributing to memory formation for neutral and emotional information.

- Investigations of the qualitative nature of memories for emotional and neutral information

  The results of Chapter 2 clearly indicated that emotional information is more likely to be vividly remembered than is neutral information. This result, however, leaves open whether the "remember" responses given to neutral words and those with valence or arousal are supported by similar types of information (e.g., Semantic associations made? Autobiographical associations? Remembering where a word occurred in a word list? Remembering a mental image created in response to the word?). It may be fruitful to provide participants with the Memory Characteristics Questionnaire (Johnson, Foley, Suengas, and Raye, 1988) to allow an assessment of the information supporting their recollective responses.

- Effects of divided attention on the neural processes recruited for encoding emotional and neutral words

  I am currently conducting an fMRI study to examine how the neural processes implicated in the formation of memories for neutral and emotional words (see Chapter 4) are affected by the divided attention manipulation. Given the results of Chapter 3, it will be of particular interest to examine whether the subsequent memory prediction in the amygdalar-hippocampal network (for arousing words) remains strong despite divided attention, while the subsequent memory prediction in the prefrontal-hippocampal network (for neutral words and words with valence only) diminishes with divided attention.

- Extension of results to nonverbal stimuli

Verbal stimuli may have unique characteristics (e.g., verbal stimuli likely are semantically processed before their threat, or lack thereof, is assessed) that make them a "special case" as to the effects of valence and arousal. Words provided an excellent first attempt to address these questions because of their ability to be matched on a range of characteristics known to influence memory, and also because it is relatively easy to find words that have valence only, and not arousal. It will be more difficult to create a large stimulus set of pictorial stimuli that meet these requirements; however, extension to different stimulus sets will be critical for furthering our understanding of how valence and arousal affect the processes contributing to memory formation.

- Memory for items with valence only or arousal in aging

Much of my research, not reported in this dissertation, has focused on memory changes in aging and age-related disease. As aging is thought to reduce the ability to use controlled encoding processes, it will be of particular interest to examine whether aging disproportionately affects the qualitative memory enhancement for items with valence as compared to those with arousal. Preliminary data suggests this to be the case. However, further studies will be needed to clarify the generality of the effect, and to examine the neural processes affected by aging that may mediate this reduction in enhancement for items with valence only.

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