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Illusions of Memory

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Parts of seperate experiences are often confidently remembered as having occurred within a single previous experience. These illusions (called "memory conjunction errors") indicate that stimuli are encoded in memory as sets of parts that can be miscombined during retrieval. Binding is the process by which stimulus parts are inter-associated in memory so that they are subsequently remembered together. Memory conjunction research reviewed here indicates that division of attention, medial-temporal brain damage, and aging all tend to interfere with binding but not with encoding of stimulus parts. Theoretical and applied implications of these findings are discussed.

Keywords: binding, memory illusions, neuropsychology, recall and recognition

It is common knowledge that memory is not always accurate; however, it is only recently that psychologists and neuroscientists have begun to delineate the diverse ways that memory may go astray. A current approach in memory research is to study specific "memory illusions," which occur when a person confidently remembers something that never happened (Roediger, 1996). For instance, subjects often confidently and incorrectly report having seen a stop sign at the scene of an auto accident if one is suggested in a postevent questionnaire (Loftus, Miller, & Burns, 1978), or a "theme word" such as *needle* after hearing a list that did not contain it but contained many of its associates (*thread*, *haystack*, etc.; Deese, 1959; Roediger & McDermott, 1995). Several journals have recently devoted entire issues to memory illusions (e.g., *Journal of Memory and Language*, 1996; *Cognitive Neuroscience*, 1999) because there is widespread belief that understanding the processes that give rise to these errors will shed light on the cognitive and neural processes involved in normal memory.

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Reinitz, Lammers, & Cochran (1992) reported a type of memory illusion that they called *memory conjunction errors*. These occur when people confidently claim to have studied a stimulus that they never experienced, but that is constructed entirely of parts of previously experienced stimuli—for instance, if subjects study the words *toothpaste* and *heartache*, they may later confidently claim to have seen the word *toothache*. These errors have been the focus of much recent research because they bear directly on the relationship between memory for stimulus parts and memory for whole stimuli. More specifically, the finding that parts of separately experienced items may be miscombined in memory has important implications. First, it implies that stimuli are encoded into memory as sets of parts. If this were not true, then there would be no way for those parts to be subsequently miscombined. Second, if memories are parts-based, then those parts must be bound together in memory. Binding is the name commonly given to the process by which items are interassociated in memory, so that parts belonging to a single experience tend to be remembered together. Memory conjunction research is therefore informative regarding the nature of the units that are encoded into memory, and the processes by which those units are bound.

The goal of this article is to review relevant research to support the following interrelated theoretical assertions: (1) Memories for both complex events (such as a trip to a restaurant) and simple stimuli (such as a face or a word) are constructed at the time of recollection from stored simple units (such as receiving a menu, or a specific nose); (2) Units encoded from separately experienced stimuli can be miscombined during recollection, resulting in a memory that does not correspond to any specific item, but rather is an amalgam of separately experienced items (e.g., Bill's nose on Jack's face); (3) The cognitive processes (and corresponding neural mechanisms) involved in encoding stimulus parts into memory are separate and independent from the processes by which those parts are bound. As a result, some factors may selectively interfere with binding. These include medial-temporal brain damage, division of attention, and aging; (4) Binding requires the involvement of both the hippocampus and conscious executive processes subserved by prefrontal cortex. Both division of attention and aging exert their effects by reducing frontal lobe involvement in memory encoding.

EMPIRICAL PRECEDENTS: EVIDENCE FOR PARTS-BASED MEMORY

Memories for Events

There is substantial evidence that remembering complex events centrally involves a constructive process in which relevant units of information residing in memory are "pasted into" a recollection of the event. Although the units that serve as the building blocks for recollections are all present in memory, they may not have been encoded from the event that is being remembered. For example, the first widely cited report of memory illusions was by F. Bartlett (1932). His subjects read a Native American story and were asked to reproduce it. As the retention interval increased, subjects were increasingly likely to unknowingly replace forgotten parts of the text with semantic information from their own memories—for instance, subjects remembered a seal-hunting scene as a fishing scene. Bartlett proposed that through experience, people develop schemas in memory. These are durable memory representations that contain information about typical events and situations. Schemas enable people to fill in gaps in their memories and guide interpretation of ongoing experiences. A multitude of subsequent findings indicate that people incorporate their own knowledge and expectations into their memories for events, for both text (e.g., Bower et al., 1979) and for visually presented scenes (Friedman, 1979; Hannigan & Reinitz, 2001). Information that is neither schema-based nor event-based may be incorporated into memories as well. For instance, suggestions made following an event may be incorporated into one's memory for the event (Schooler et al., 1986). Moreover, actions that were causally inferred during an event may later be remembered as having been specifically witnessed. In a recent study by Hannigan and Reinitz (2001), subjects viewed slide sequences depicting typical events, for example, a trip to the grocery store. Each sequence contained a "causal staging scene" that implied some cause—for instance, people might see a woman picking up oranges from the floor of the produce section. Subjects later received a slide recognition test that included cause scenes that were implied but never witnessed, for example, a woman plucking an orange from the bottom of a stack. Although these slides were new, subjects had a very strong tendency to claim that they were old. All of this research makes it very clear that memories for complex events are not like videotapes that are reviewed at the time of recollection. Rather, they are interpretative constructions built from a variety of informational sources, including information encoded from the event itself, entries contained in schemas, causal inferences, and information acquired about an event after the fact.

Memories for Individual Stimuli

In contrast to extensive research demonstrating the parts-based nature of memory for complex events, relatively little research addressed the possibility that memories for individual stimuli such as words, faces, and objects might be constructed from stored simple units. However, some research was suggestive of this possibility. For instance, Brown and McNeill (1967) demonstrated that a person may fail to retrieve a word and still correctly report both its first letter and the number of syllables it contains.

Similarly, people who fail to recall a word on a previously studied list may nonetheless be able to name semantic associates of that word (Eysenck, 1979). These findings imply that memories for words are multidimensional rather than unitary, such that some word features (syllables, meaning, first sound) are quasi-independent in that they can be retrieved in the absence of the others.

Underwood and colleagues performed experiments that provided direct evidence for parts-based representations for words. Underwood and Zimmerman (1973) showed that subjects made more false recognition responses to test words that shared syllables with previously studied words than to test words that did not share syllables with study words. Underwood et al. (1976) showed that subjects made more false recognition responses to compound words that contained component words that had been studied earlier than to compound words that did not contain old components. On the basis of these findings, Underwood and colleagues concluded that words are represented in memory as sets of smaller units that include syllables and individual words (in the case of compounds).

Finally, the specific formal models of memory that were developed in the 1980s and 1990s are relevant to the issue of parts-based representations for single objects. Although a review of these models is beyond the scope of this article, it is worth pointing out that virtually all recent models of memory assume that objects are represented as collections of smaller features. This is clearly seen in the distributed representational schemes employed by competitive-activation models that represent visual words as letter sets and spoken words as sets of phonemes (e.g., McClelland & Rumelhart, 1981; McClelland & Ellman, 1985) and the related set of adaptive resonance models proposed by Grossberg and his colleagues (e.g., Carpenter & Grossberg, 1986) and by Wang and Reinitz (2001). "Holographic" models based in correlation and convolution also represent objects as sets of units, each typically represented as an integer value in an array that represents the object (Murdock, 1982; Metcalfe Eich, 1982). Although these models are in themselves theories, and so do not provide direct evidence regarding the nature of stored memories, their preponderance suggests the utility of parts-based memory representations for stimuli.

MEMORY CONJUNCTION ERRORS: PARADIGM AND BASIC FINDINGS

The experimental paradigm used to test for memory conjunction errors is an adaptation of a procedure originally devised by Treisman and colleages (Treisman & Gelade, 1980; Treisman & Schmidt, 1982) for studying visual perceptual representations of objects. Those authors tested the idea that visual features such as color, form, and location are separately and independently acquired by the visual system. If this is so, then there must be a process that occurs following feature acquisition, by which separately encoded features are conjoined into percepts (a process now referred to as perceptual binding). They presented subjects with arrays of colored letters for brief durations, and asked them to report what they saw. They found that subjects rarely reported colors or letters that were not contained in the array (they rarely made "feature errors") but often reported miscombinations of colors and letters—for instance, they might report having seen a red *o* when a green *o* a red *x* had been presented. Treisman and colleagues called these erroneous reports "conjunction errors". Based on the high rate of conjunction errors relative to feature errors, Treisman and colleagues concluded that visual experiences are constructed from independently encoded perceptual features, and that those features can be miscombined to create perceptual illusions.

Reinitz et al. (1992) adapted this paradigm to test the notion that memories of stimuli are constructed from separately represented simple units. In their experiments, subjects studied sets of stimuli until they had memorized them. Memory for the stimuli was later tested in an "old"/"new" recognition test that included four types of test stimuli. Old stimuli had been previously studied. Conjunction stimuli were new stimuli constructed entirely from previously studied stimulus parts. Feature stimuli contained some previously studied and some new parts. Finally, new stimuli did not contain any previously studied parts. The underlying logic was that if subjects made relatively many false "old" responses to conjunction items, and relatively few "old" responses to feature stimuli, this would indicate that memories are encoded as sets of parts rather than as indivisible wholes. The reason is that there would be no way for subjects to miscombine parts of previously studied items unless those parts were separately represented and conjoined during recollection to form memories for previously studied stimuli.

Experiment 6 from the Reinitz et al. (1992) study provides an example. In that experiment subjects first studied a set of line drawings of faces and then received a recognition test containing old, conjunction, feature, and new faces. Faces were used as a conservative test, because of the many findings from neuroscience indicating the special "holistic" nature of face recognition (e.g., Diamond & Carey, 1986; Farah, 1994). Examples of these stimuli are shown in Figure 1. The results are shown in Figure 2, and are quite typical—subjects did not make significantly more false recognition responses to feature faces than they did to completely new faces; however, for conjunction faces (comprised entirely of old facial features) there was a very high rate of false recognition. Essentially identical patterns of results were obtained when the stimuli were two-syllable nonsense words. Based on these results, Reinitz et al. concluded that these types of stimuli were represented in memory as sets of parts that were conjoined at the time of recollection on the basis of stored interpart associations (binding). Further, they concluded that it is easier to encode (or to remember) parts than to encode (or remember) between-part associations. As a result, parts are sometimes remembered but miscombined, resulting in memory conjunction errors.

FIGURE 1 Examples of face stimuli used by Reinitz et al. (1992) and many other authors. The face on the right is a conjunction face constructed from the left and middle faces.

Subsequent research has demonstrated the very broad generality of these findings. Patterns of results similar to the pattern shown in Figure 2 are obtained when stimuli are syllables from separately studied words (*barter, valley*: *barley*; Kroll et al., 1996); compound words (e.g., *stargaze, catfish*: *starfish*, Reinitz & Demb, 1994); photographs rather than line drawings of faces (Bartlett & Searcy, 1998), and even buildings from separately

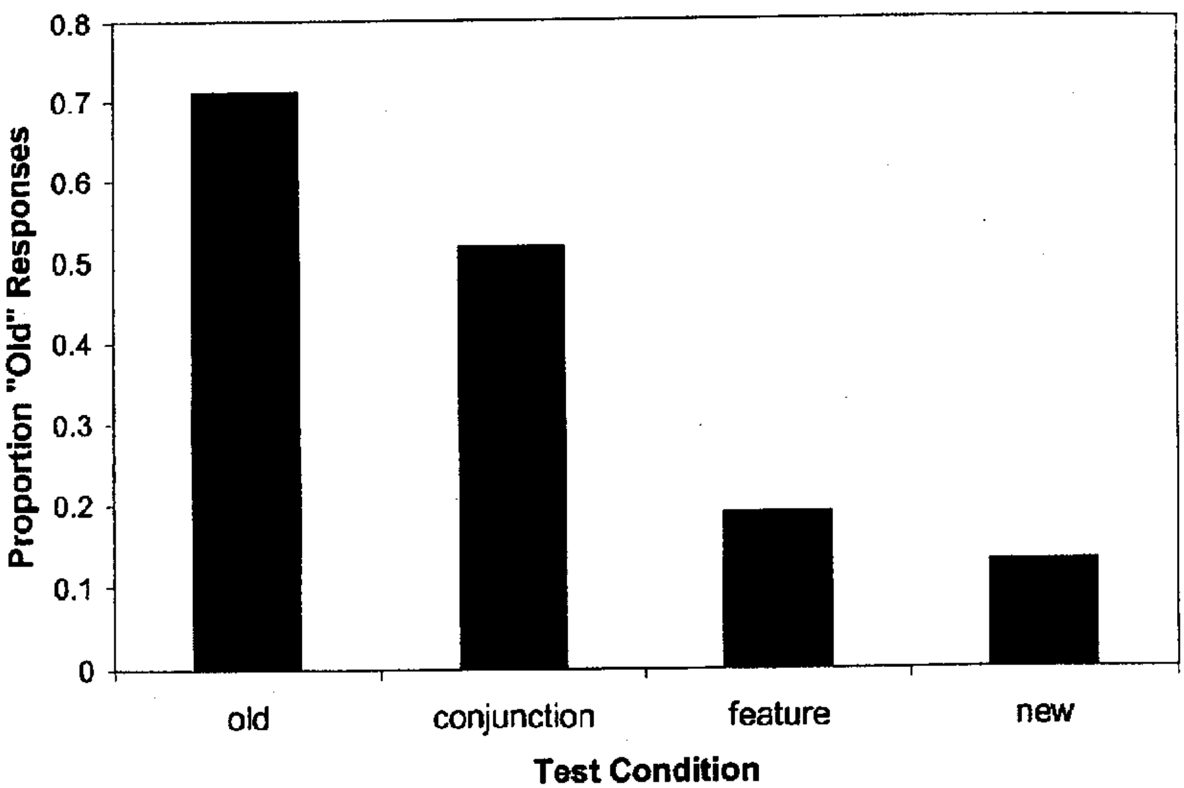

FIGURE 2 Proportion of "old" responses for each of the four types of recognition test items. Very similar patterns of results have been obtained for a broad variety of stimuli. Data from Reinitz et al. (1992, Experiment 6).

experienced environments (Albert et al., 1999). In addition, high rates of conjunction errors are found in both recognition tests and in recall (Reinitz et al., 1992; Reinitz & Hannigan, submitted). Together, these experiments suggest that a very broad range of stimuli is encoded in memory as sets of parts that must be recombined at the time of the memory test.

ROLE OF ATTENTION

The memory conjunction paradigm has been extensively employed to investigate the role of attention in encoding memories. The research supports the theoretical proposals that attention is relatively unimportant for encoding stimulus parts into memory, and that attention has the function of binding stimulus parts in memory. These proposals are supported by experiments in which subjects are unable to attend to items presented during the study phases of recognition experiments, and by experiments in which subjects attend to more than one item at a time during the study phase. These experiments are reviewed here.

There is substantial evidence that when attention is divided during the study phase, subjects encode stimulus parts but fail to bind them. As a result, they are sensitive to old stimulus parts, but not old combinations of parts, during the memory test. Reinitz et al. (1994) presented subjects with a series of faces to remember. Some (full-attention) subjects were able to attend to the faces while they were presented. Other (divided-attention) subjects were required to count rapid dot sequences that were presented on the faces. As a result, both subject groups looked at the faces, but only the full-attention subjects were able to attend to them. There were two important findings. First, divided-attention subjects were not significantly less able than full-attention subjects to reject partially or completely new stimuli. Such rejections require the ability to detect the presence of new stimulus parts; thus divided-attention subjects were not impaired in their abilities to discriminate old from new parts. This implies that stimulus parts were successfully encoded into memory.

The second important finding was that, unlike full-attention subjects, divided-attention subjects were unable to discriminate old stimuli from conjunction stimuli. For subjects to make this discrimination it is not sufficient to remember old parts, because all of the parts in both stimulus types were presented previously. Instead, it is necessary to have bound the parts so that they are remembered as having occurred together.

These findings indicate that when attention is divided, subjects will subsequently remember old stimulus parts, but will fail to remember how those parts had been interrelated during the study phase. This implies that attention is important for binding parts in memory, but not for encoding those parts. Other experiments involving division of attention have also supported the claim that attention plays a central role in binding. For instance, Jacoby et al. (1989) showed that subjects who studied novel names in a divided attention condition later judged those names as famous, presumably because they encoded the names into memory, but did not bind them to the study context in which they occurred. Subjects in a full-attention condition did not subsequently judge the names as famous. In addition, several authors have recently replicated and extended the findings of Reinitz et al. (1994). For instance, Jones and Jacoby (2001) showed that dividing attention during the memory test rather than during the study phase also reduces subjects' ability to discriminate old from conjunction stimuli. This indicates that attention is important for retrieving, as well as for encoding, information about binding.

A different approach to studying the role of attention has been to have subjects attend to more than one stimulus at a time during the study phase. Reinitz and colleagues (Reinitz, Morrissey, & Demb, 1994; Reinitz & Hannigan, 2001) proposed that attention binds together the stimulus parts that it contacts. As a result, they predicted that if two stimuli are attended simultaneously, their parts will be bound together into a single memory representation, such that it will be hard for subjects to segregate those parts into recollections of the individual stimuli that had originally contained them (this has been called the "overbinding" hypothesis). Several recent experiments support this prediction. For example, in experiments by Reinitz and Hannigan (2001), pairs of faces were presented during the study phase of the experiment. For some subjects, faces within each pair could be attended together, because the pair members were presented simultaneously (one just above the other) for 8 s. For other subjects the pair members were attended sequentially, because the faces within each pair were presented one after the other, for 4 s each. In both cases, the face pairs were separated by 10-s blank intervals.

The subjects subsequently received a recognition test that contained old and new faces as well as two types of conjunction faces. Within-pair conjunction faces were constructed from parts of parent faces that had occurred in the same study pair, and between-pair conjunction faces were constructed from parent faces that had occurred in separate study pairs. Subjects in the simultaneous-presentation condition had substantial difficulty discriminating old faces from within-pair conjunction faces, as indicated by the very high false alarm (i.e., "old" responses to new items) rate to within-pair conjunction faces in that condition. Subjects in this condition made few false alarms to between-pair conjunction items. Thus the surprising finding is that when faces are studied simultaneously, subjects are subsequently quite good at remembering which study pair contained specific facial features (as indicated by the low between-pair conjunction error rate) but have great difficulty remembering which face within the pair contained specific features (as indicated by the high within-pair conjunction error rate). There were many fewer false alarms to within-pair conjunction faces for subjects who had studied the faces sequentially. Moreover, those subjects had equal false alarm rates for between-pair and within-pair conjunction faces. This indicates that there was not differential binding of within-pair facial features in the sequential presentation condition, which is to be expected, as pair members were not attended together in this condition. The features of within-pair faces are apparently bound into separate face representations in the sequential presentation condition, but into representations of the whole study pair in the simultaneous-presentation condition.

A related finding was reported by Hannigan and Reinitz (1999). Those authors tested recognition of simultaneously presented faces either 15 min or 24 h after the study session. The data are summarized in Figure 3. As can be seen, the specific effect of increasing the retention interval was to increase false "old" recognition responses to within-pair conjunction faces, such that those faces could not be discriminated from old faces. This strongly supports the notion that parts of simultaneously studied faces are inextricably bound into a single memory representation of the study pairs. After 24 h the episodic information that mediates discrimination between old and within-pair conjunction items is forgotten. As a result, subjects can remember which facial features had occurred within the same face pair, but not the individual faces that had occurred within the pair.

A variety of recent findings confirm the notion that parts of co-attended items are bound together in memory. Reinitz and Hannigan (submitted)

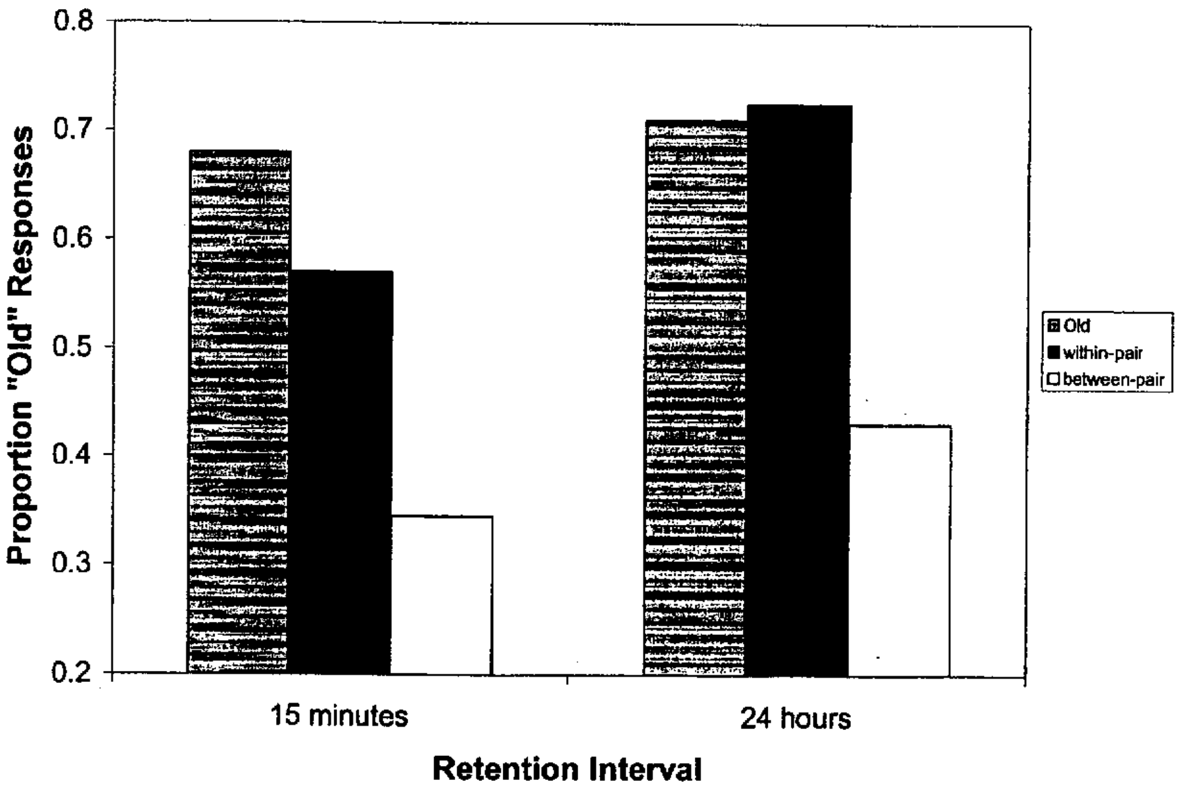

FIGURE 3 Effect of retention interval on recognition memory for old faces, within-pair conjunction faces, and between-pair conjunction faces. Data from Hannigan and Reinitz (1999).

showed that the effects of sequential versus simultaneous presentation described above for faces also occur for compound words. Finally, Reinitz and Hannigan (2001) showed that when the members of a study pair alternated back and forth (e.g., A–B–A–B), subjects subsequently had difficulty discriminating within-pair conjunction faces from old faces in the recognition test. The same subjects could easily reject between-pair conjunction faces. When pair members did not alternate back and forth during the study phase (e.g., A–A–B–B), subjects did not show this selective discrimination difficulty; in this case, there were equal and moderate false alarm rates to both types of conjunction faces. Thus when attention is shifted back and forth between study faces, the parts of those faces are subsequently remembered together.

All of this research strongly supports the idea that attention binds whatever it contacts. When attention is divided, binding does not occur. When items are attended together, all of their parts are bound together into a single, chunked memory representation, such that those parts cannot subsequently be accurately segregated into recollections of the individual items that contained them.

EFFECTS OF HIPPOCAMPAL DAMAGE AND AGING

In addition to division of attention, both medial-temporal brain damage and aging appear to selectively interfere with binding, while leaving encoding of stimulus parts relatively intact. The evidence is reviewed briefly next.

Effects of Medial-Temporal Damage

It is well known that damage to the hippocampus or surrounding regions produces profound memory deficits. In an influential and comprehensive review of the literature regarding learning and memory following hippocampal damage, Johnson and Chalfonte (1994) proposed that the fundamental role of the hippocampus is to form new associations between preexisting elements in memory (i.e., binding), rather than to encode new simple units. Similar proposals have been made by many others, including Cohen and Eichenbaum (1993), Eichenbaum and Bunsey (1995), Moscovitch and Winocur (1992), and more recently Moscovitch (2000).

Given this view, people who have become amnesiacs as a result of medial-temporal damage should have great difficulty discriminating old stimuli from conjunction stimuli because they should fail to encode the between-feature associations that are required to make this discrimination. In addition, if encoding of stimulus parts is relatively unimpaired, then these amnesiacs should retain the ability to reject partially and completely new stimuli, as these rejections do not require binding. Reinitz et al. (1996) tested these predictions. Their subjects were 12 profoundly amnesic patients with intact attentional capabilities at the Memory Disorders Research Center at the

Boston Veterans Administration (VA) hospital, and 24 control subjects who were matched with the amnesiacs in age, sex, IQ, education, and history of alcohol use. The subjects studied a series of compound words, and 3 min later received a recognition test containing old, conjunction, feature (partially new), and completely new words. The results of one of the experiments is shown in Figure 4. In the figure, the baseline false alarm rate (i.e., the frequency of "old" responses to new test items) has been subtracted from the "old" response rates from the other conditions to correct for differential false alarm rates between the groups. As can be seen, amnesiacs and controls were equally able to reject feature words. This suggests that the amnesiacs encoded the parts of the words that they had studied. However, unlike the control subjects, the amnesiacs were unable to distinguish old from conjunction words. This supports the proposal that parts were encoded but not bound.

A similar finding was reported by Kroll et al. (1996), who showed that strictly unilateral hippocampal damage may be sufficient to eliminate binding entirely. Seven of their patients had damage to their hippocampal systems that was restricted to the left side, and eight had damage only on the right side. Memory in these patients was tested using several types of stimuli.

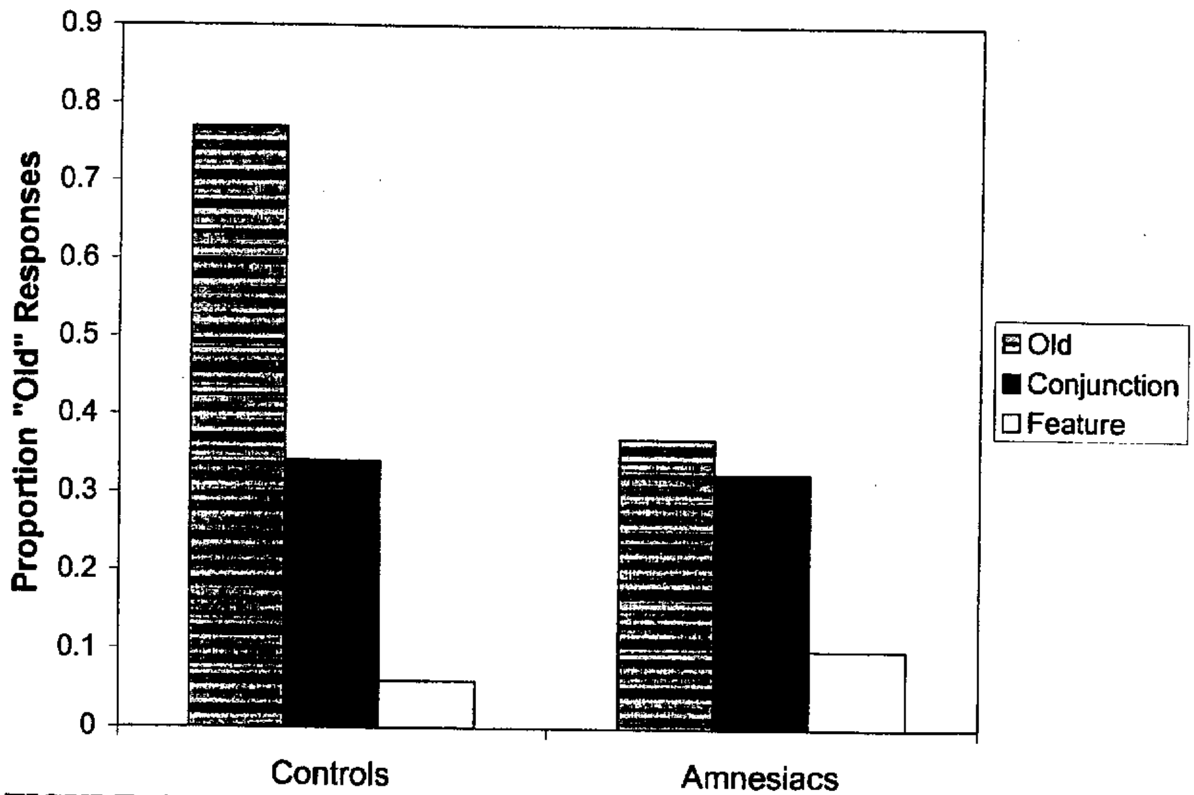

FIGURE 4 Data from Reinitz et al. (1996) showing the effect of hippocampal damage on recognition of old words, conjunction words, and feature words. Data are for amnesiacs and controls. For each group, the baseline false alarm rate (i.e., rate of "old" responses to new words) has been subtracted from the rate of "old" responses in each of the other conditions to control for differential baseline false alarm rates.

When the set of faces used by Reinitz et al. (1992, 1994) were tested, the subjects responded that old, conjunction, and feature faces were "old" on 72.1, 71.45, and 39.3 percent of the trials, respectively. That is, these subjects retained the ability to reject faces that contained new features, but were completely unable to remember the specific features that had occurred together.

To date, the data and the dominant theories support the notion that the function of the hippocampus is to bind stimulus features in memory. However, a minority of researchers support an alternative theoretical view by which representations of stimulus parts and whole stimuli are simultaneously and independently encoded into memory (e.g., Rudy & Sutherland, 1994). This multiple representations view proposes that whole stimuli may be identified on the basis of memories for their component parts, or instead on the basis of a unitary memory of the entire stimulus. By this view the hippocampus is centrally involved in the construction of holistic stimulus representations, so that in the case of hippocampal damage patients must recognize stimuli on the basis of their parts alone. Although this view is losing popularity as more becomes known, at this point it cannot be completely ruled out.

Effects of Aging

It is common knowledge that aging results in memory deficits. Although there are various theoretical explanations for these age-related changes, there is increasing support for the notion that they are the result of reduced attentional capacity* resulting from decreased dopamine and decreased frontal lobe activation during memory encoding in the aging brain (e.g., Craik, 1982; Braver et al., 2001). One would therefore expect aging to produce patterns of memory deficits similar to patterns observed for young adults under conditions of divided attention. More specifically, aging should selectively interfere with binding.

One type of support for this prediction comes from source-monitoring experiments. Source monitoring errors occur when a person remembers an item, but fails to remember the context in which the item was encoded (Johnson et al., 1992). Such errors reflect a failure to adequately bind items to their context. There is much evidence for increased source monitoring errors with increasing age (e.g., Chalfonte & Johnson, 1996; Schacter et al., 1991). It is easy to see how reduced memory for source may interfere with the lives of older people; for instance, older adults sometimes report difficulty remembering whether they had actually taken their medication, or only

*Attention is complex, and different types of attention are mediated by different neural structures. The term is used here to refer to conscious executive control functions associated with working memory (e.g., Goldman-Rakic, 1995).

thought about taking it. This decrease in source memory with age has generally been interpreted as evidence for decreased binding.

Recently, Castel and Craik (submitted) used a memory conjunction paradigm to directly compare the effects of aging and divided attention on recognition memory. They found that, relative to young adults tested under conditions of full attention, both older adults and young, divided-attention subjects showed a marked inability to distinguish old from conjunction items. In addition, they failed to find evidence for a marked decrease in memory for stimulus components.

The data are consistent with the proposal that aging selectively impairs binding. Moreover, there is substantial evidence that this impairment is attentional in nature. The patterns of memory deficits associated with aging mimic those that are obtained when attention is divided. Furthermore, source memory has been demonstrated to depend upon the integrity of the frontal lobes (Glisky et al., 1995; Janowsky et al., 1989), which have in turn been shown by many authors to play a central role in conscious attentional processing. Several authors have demonstrated that there is decreasing frontal-lobe activation during memory encoding with increasing age (for a review see Raz, 2000). This decrease is associated with decreasing availability of dopamine, which is known to mediate high-level attentional processes (Braver et al., 2001). Moscovitch (2000) recently proposed that binding involves both attentional processes mediated by the frontal lobe, and nonconscious, automatic processes mediated by the hippocampal system. The results reviewed in this section support this proposal. Hippocampal damage interferes with binding despite normal attentional capabilities, whereas both division of attention and aging appear to interfere with binding by reducing frontal lobe activity. The specific manner in which these mechanisms interact remains unknown.

ALTERNATIVE THEORETICAL EXPLANATIONS

There has been recent controversy regarding the underlying mechanisms that give rise to memory conjunction errors. Reinitz and colleagues have repeatedly proposed that stimulus parts may be miscombined during recollection, giving rise to consciously held false memories that contain parts of separately experienced stimuli (this is subsequently referred to as the recollection-based explanation). Several authors have alternatively proposed that these errors are the result of familiarity in the absence of conscious recollection. The idea is that parts of old items will give rise to familiarity. As the number of old parts that are present in a stimulus increases, so will the familiarity that is engendered by the stimulus. If subjects fail to remember the original stimuli that contained those parts, then this familiarity would produce a tendency to respond that conjunction stimuli are old. Like recollection-based explanations, familiarity-based explanations assume that stimuli are encoded as sets of parts—if this were not so, then individual parts would not match their memory representations, and so would not give rise to familiarity. The important difference between them regards whether memory conjunction errors result from false consciously held recollections, or instead from merely a feeling of familiarity.

Several sources of evidence support the familiarity explanation. For instance, Jones and Jacoby (2001) provided evidence that some manipulations known to affect recollection but not familiarity tend to influence "old" responses to truly old stimuli, but not to conjunction stimuli. For instance, forcing subjects to make a recognition response within 850 ms of the onset of a test item influenced responding to old, but not to conjunction, words relative to a condition where subjects had more time to respond, presumably because they were forced to rely on familiarity when they did not have time to think back on their prior experiences. On this basis, Jones and Jacoby argued that recognition responses to old stimuli are based in conscious recollection, and that "old" responses to conjunction items are based in familiarity.

Similarly, Rubin et al. (1999) showed that event-related potentials (ERPs) accompanying false alarms to conjunction stimuli were more similar to ERPs accompanying false alarms to new stimuli than to ERPs accompanying hits to previously presented stimuli. Based on this, the authors proposed that the neural processes that give rise to false recognition responses to conjunction items are different from those involved in recognizing old items (which presumably involve conscious recollection). It is possible that false alarms to conjunction items may sometimes result from familiarity, and may other times result from recollection—if this is so then the authors may have summed ERPs from both familiarity-based and recollection-based responses in the conjunction condition; nonetheless, the results are consistent with the proposal that conjunction errors are not always the result of false conscious recollection.

Despite these findings, there is considerable evidence that memory conjunction errors often reflect false consciously held memories rather than mere familiarity. For instance, Reinitz and Hannigan (submitted) showed that memory conjunction errors frequently occur in recall. Their subjects studied a series of simultaneously presented or sequentially presented compound-word pairs and then received a free recall test, in which they were asked to write down as many words as they could remember from the study list. Subjects in the simultaneous-presentation condition "recalled" conjunctions of within-pair compound words 20 percent of the time, and subjects in the sequential-presentation condition never reported conjunctions of within-pair words. This supports the previous assertion that parts of separate stimuli are bound together in memory when those stimuli are attended together. Reinitz et al. (1992) showed that subjects often miscombined the subject of one memorized sentence with the object of another in free recall. Such errors are likely to result from false recollection, rather than from familiarity, since there is no test item provided in recall tests to engender familiarity in the first place (but see Gillund & Shiffrin, 1984). Other more colloquial examples of recall errors (e.g., "mixed metaphors") imply that stimulus parts are sometimes miscombined into false recollections during retrieval.

Effects of proximity on the study list on recognition memory provide additional evidence that memory conjunction errors are not due exclusively to familiarity. In several articles we have demonstrated that subjects make more conjunction errors to stimuli whose parent items were presented together in the study list than to stimuli whose parents had been distant from one another on the study list. All of the parts of previously studied items should later seem about equally familiar; as a result, conjunction items should be equally familiar regardless of whether the parents were close together or far apart in the study list. Familiarity-based explanations therefore have great difficulty accounting for these proximity effects.

Finally, Reinitz et al. (1994) specifically asked their subjects to judge whether each of their recognition responses was accompanied by a specific recollection of a prior experience (by responding "remember") or whether the reponse was instead based on a feeling of familiarity (by responding "know"). Under conditions of full attention, subjects claimed to recollect conjunction faces more often than they claimed to respond on the basis of familiarity.

Complex mental phenomena are often mediated by multiple underlying mechanisms. Familiarity-based and recollection-based explanations for memory conjunction errors are therefore not mutually exclusive. There is significant evidence that both types of processes sometimes contribute to these errors, and this is the position most commonly advocated by authors on both sides of the debate (e.g., Reinitz & Hannigan, 2001; Jones & Jacoby, 2001).

SUMMARY AND RELEVANCE

Theoretical Implications

Research employing the memory conjunction paradigm and related paradigms indicates that events and simple stimuli are stored in memory as sets of parts. Those parts must be bound together in memory so that they are remembered together later on. When binding information is poorly encoded, or is inaccessible at the time of retrieval, memory conjunction errors occur, in which parts of separately experienced objects or events are conjoined into a false memory that is an amalgam of past experiences.

Encoding and retrieval of binding information are more vulnerable to disruption than are encoding and retrieval of stimulus parts. Three factors have been identified that selectively interfere with binding; these are division of attention, medial-temporal brain damage, and aging. These factors exert their effects at two different neural loci. Hippocampal processing appears to be necessary for binding, so amnesia resulting from medial-temporal brain damage is characterized by a severe binding deficit. Encoding of individual stimulus parts seems to be relatively preserved in these patients. Conscious processing mediated by prefrontal cortex also appears to be necessary for binding. As a result, division of attention selectively interferes with binding. Moreover, shared attentional processing of multiple stimuli produces a phenomenon called overbinding, in which parts of those stimuli are bound into a single memory representation such that it is subsequently hard to "separate out" those parts into memories of the individual stimuli that had originally contained them.

Like division of attention, aging appears to exert its effect on binding by reducing activity in frontal cortex when stimuli are encoded into memory. This is probably the direct result of reduction in the neurotransmitter dopamine, which is centrally involved in frontal lobe attentional processes. Braver et al. (2001) recently proposed that reduced dopamine gives rise to poor encoding of context, and argued that this binding impairment could give rise to many of the cognitive deficits associated with aging. To the extent that this argument is correct, binding failures are likely to give rise to a wealth of real-world problems.

Finally, it has been noted that memory conjunction errors occur across a very broad range of stimuli, and are manifested in both recognition and recall tests. Rather than being isolated phenomena, they seem to constitute a "general rule" of memory. This implies that the same memory mechanisms are employed for encoding and remembering many different types of stimuli, across many types of situations.

Applied Implications

In addition to providing theoretical insight into the workings of memory, memory conjunction research has applications outside of the laboratory. Given the generality of the effect, such errors are likely to occur often in the real world. For instance, witnesses to a crime may miscombine parts of the perpetrator's face (or parts of a license plate number) with parts of another individual's face (or parts of another license plate). In such cases the witnesses are likely to be confident in their erroneous report, as previous research has shown that warning subjects about the possibility of making conjunction errors does not reduce the frequency of, or confidence in, such erroneous memories (Reinitz et al., 1992). It is therefore useful to know when such errors are likely to occur. The research reviewed here indicates that memory conjunction errors are most likely when stimuli are attended together. As a result, witnesses should be more likely to miscombine parts of items present at the crime scene than to miscombine parts of items that occurred in separate episodes. Furthermore, if the attention of a witness is divided while the crime is occurring (say because the witness is intently focusing on a weapon), there is an increase in the likelihood of memory conjunction errors. The research also indicates that these errors increase with the passage of time. This has direct relevance to the courtroom, as cases typically go to trial many months after the crime occurred. Finally, older adults are more prone than younger adults to make these errors.

The finding that older adults tend to suffer from a binding impairment raises real-world issues. As previously noted, poorer source memory may produce difficulties for older people, for instance, in remembering whether they took their medication. Age-related binding difficulties are very probably the result of reduced attentional capacity in these individuals. It is therefore likely that training older adults to more deliberately attend to important items and events would help to reduce these problems.

Final Comment

The previous paragraphs indicate that encoding memories as sets of parts results in potential real-world problems. More generally, it has recently become clear that a wealth of independent memory illusions occur, indicating that there are many ways in which false memories may arise. A common debate these days in the memory literature regards the issue of whether memory is "good" or "bad," with some authors highlighting the inaccuracy and malleability of memories (e.g., Loftus, 1997) and others highlighting the adaptive functionality of memory (e.g., Hannigan & Reinitz, 2001). Two considerations that bear on this issue are human functionality and the benefits that might accrue from parts-based representations. People generally function exceedingly well—they are able to survive, to reliably perform high-level occupational functions, and to develop rich social networks. All of this implies that memory functions well for purposes it has been adapted for. One might argue that the cases where normal memory tends to fail are unusual, and have requirements that are unrelated to survival and functionality. For instance, much evidence indicates that memories are interpretations rather than objective records of events; however, there are few instances in the real world in which it is necessary to recall facts in a manner that is divorced from interpretation. One exception is the case where an individual has witnessed a crime. This situation is inconsistent with the functions that memory has evolved to serve, so eyewitness accounts should generally be viewed as dubious.

Additionally, benefits result from parts-based representation. Such representations make it possible to "fill in the gaps" in memories with other units that are available in memory to serve this purpose. Memory conjunction errors show that such "filling in" can sometimes lead to erroneous memories; however, these inferences are often likely to be accurate, particularly when they are guided by top-down knowledge regarding what is typical of a stimulus or a type of event. Additionally, representing memories as parts imbues the system with flexibility that would be lacking if items and events were encoded as unitary wholes. Language is flexible because words can be ordered in various ways to represent various ideas; similarly, memory is flexible because representations of parts can be bound in various ways to represent a variety of stimuli and events. The benefits of parts-based representations far outweigh the cost of the memory illusions that they give rise to.

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