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SENSITIVITY OF RELATIONAL MEMORY REPRESENTATIONS TO THE FACTORS OF REPETITION, EMOTION, AND CONTEXT INFORMATION

BY

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Abstract

Episodic memory is the human cognitive faculty that enables humans to have a record of everyday events. Relational processing and representations are widely accepted to be the crucial underlying mechanism, implemented in the hippocampus, that support normal episodic memory function. As such, to better understand relational memory is to gain a more complete understanding of episodic memory function.

One facet of hippocampal-dependent memory under intense investigation is its interaction with other factors concomitant with episodic events. The motivation behind examining these interacting factors are three-fold: (1) to gain insight into whether, and how, such factors may be incorporated into episodic memory, (2) to shed light on the underlying organization of the episodic memory representations, and (3) to observe the ultimate consequence they have on memory performance. In this dissertation, we explore 3 factors most commonly present in episodic experiences –namely, repetition, negative emotion, and context, and the sensitivity of relational memory representations to these factors.

The first experiment examined relational memory sensitivity to repetition-induced changes in memory strength and its neural substrates as indexed by fMRI. The central objectives were to investigate whether variations in relational information strength is incorporated and represented in the hippocampus, and whether this response could be dissociated from changes in non-relational memory indexed by a separable memory region. Results from this experiment yielded evidence for both objectives and additionally provided support for the view that episodic memory may be represented in separable streams of information, such as item versus context, with dissociable neural substrates.

The second study examined the sensitivity of relational processing to the factor of negative emotion. While attention allocation is widely cited as the mechanism for the impairing or enhancing effects of negative emotion, we tested a novel hypothesis that negative emotion may specifically impair relational processing and its underlying memory organization. Eye-movement monitoring was employed as means to provide insight on attention allocation biases by emotion, and to provide a well-established, implicit measure of relational memory performance. Results showed that, under conditions of equal overt memory accuracy, response timing and visual sampling differed between negative and neutral conditions and thus provide support that negative emotion may cause relational memories to be organized or represented differently from those without negative valence.

The third study asked the question of what information properties underlie the often-invoked construct of "context" information that is an integral part of all episodic memory representations. A novel hypothesis was tested –that stability of relational information imparts context-like properties in helping organize memory representations of events, subserved by relational processing. Experiment found evidence in support of the hypothesis such that stability enhanced behavior accuracy and eye movement indices indicated greater memory for conditions with stability compare to those without.

Taken together, these experiments broaden current understanding of the sensitivity of relational memory representations to factors commonly present in episodic experiences. In the last chapter, we further synthesize the results and argue that even though the 3 experiments were cast as testing three separate factors, they may all be interpreted as investigations into various types of context information.

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CHAPTER 1: BACKGROUND AND MOTIVATION FOR STUDIES

Introduction

The mental faculty of memory has a remarkable ability to form records of our daily experiences. This mental record of events, or episodic memory, constitutes a multitude of elements with complex interrelationships that can be intermixed with emotion and can take place in varied contexts. Indeed, it is due to episodic memory that we can have access to information of the past. In contrast, amnesic patients, who are dispossessed of the ability to recollect any past memories or create new memories, can be described as being "a prisoner of consciousness", being explicitly aware only of only the present moment (Wilson & Wearing, 1995)

Research initially treated episodic memory as a unitary construct, perhaps due to the temporally-extensive and information-general manner of amnesic patients' memory impairments (Odgen & Ogden, 1996). However, advances in the sophistication of data collection methods and experiment paradigms employed have accumulated in a body of empirical evidence that point to a *componential* construct of episodic memory. As described in the brief review below, most current models and theories on episodic memory cite two components or information streams in episodic memory—(1) *item* information consisting of a current perceptual event (Tulving, 1972) and (2) other properties that are *related* to the current event, such as the temporal or spatial information, often collectively term *context* information.

Even though there is general consensus that episodic memory likely consists of item information and its related context, a detailed understanding of their computation, mental representation, and neural substrates remain topics under intense debate and research. In order to

further illuminate these aspects of episodic memory, the collection of studies detailed in this dissertation examines the characteristics of *relational* aspect of episodic memory representations. The overarching question investigated here is whether all episodic relational memory representations are created equal or if some factors common to everyday experiences can alter and influence relational memory representations. To this end, we explore how the factors of repetition, negative emotion, and manipulations of context information affect episodic memory its underlying relational representations.

We begin our investigation by a brief discussion of the significance of relational memory representations within the study of episodic memory, the status of current findings, and an explanation of the contribution this collection of studies hopes to make towards this area of memory research.

Theories of Episodic Memory

Research on episodic memory first began with a neuropsychological approach, by studying amnesic patients with impaired episodic memory. These studies identified the bilateral hippocampus (HC) residing within the medial temporal lobe (MTL) regions of the brain as critical for the formation of memory (Cohen & Squire, 1980; Milner, 1966; Scoville & Milner, 1957). Furthermore, by comparing and contrasting the pattern of preserved versus impaired memory functions in amnesic patients, the discovery was also made that there are multiple separable memory systems, and that HC damage specifically impairs *declarative* memories which include episodic memory (Cohen & Eichenbaum, 1993; Cohen, Poldrack, & Eichenbaum, 1997; Eichenbaum & Cohen, 2001; Squire, 2004; Squire & Zola-morgan, 1991).

At the same time, theories have also advanced based on cognitive psychology methods centered on carefully examining and accounting for participants' behavioral performance and subjective assessments of the quality of their memories. One type of behavioral index extensively employed in cognitive psychological studies of memory is the distinction in subjective feelings associated with episodic memory, such as the feeling of "knowing" that something is familiar versus being able to "remember" some event definitively, which is typically accompanied by recall of additional confirmatory relational or contextual information.

A class of theories that has been motivated by such subjective memory distinctions is one that attempts to unravel the underlying cognitive process(es) involved. Single-process theories (also "signal-detection" theories) argue that episodic memory is subserved by a single type of mental computation and mental representation which varies in strength (Wais, 2008; Wais, Wixted, Hopkins, & Squire, 2006; Wixted, 2007). The varying strengths in the memory representation give rise to different subjective confidence levels that, in turn, lead to different behavior responses. Specifically, memory with lower subjective confidence believed to index weaker underlying signals are endorsed as "know" by participants, and memory with higher subjective confidence believed to index stronger underlying signals are labelled "remember". Dual-process theories, on the other hand, propose that differences in subjective assessment of episodic memory stems from two *qualitatively* different types of memory computations and representation. One type consists of item-based information, leading to a sense of familiarity, while the other type encodes relational or contextual information concomitant to the item, resulting in recollection and a feeling of remembering (Brown, Warburton, & Aggleton, 2010; Eichenbaum, Otto, & Cohen, 1994; Rugg & Yonelinas, 2003; Yonelinas, 2002; Yonelinas, Kroll, Dobbins, Lazzara, & Knight, 1998) .

A Cognitive Neuroscience Model of Episodic Memory

To adjudicate between the above-mentioned competing theories, researchers have used a variety of response function models with either single or dual-process assumptions in hopes of identifying one that may better explain the behavior data j(for review, see Yonelinas & Parks, 2007). However, this effort has yet to produce a widely accepted conclusion, in part because each class of models best explains different subsets of the data (for review, see Malmberg, 2008). Therefore, there is a need for additional data to supplement behavioral findings to support further testing of different episodic memory theories. Fortuitously, with the advent and advances of functional resonance imaging (fMRI), psychologist have gained the ability to obtain high spatial resolution neuronal activity during active participation in tasks. Thus, neuroimaging evidence has become a powerful contributor of additional and unique data that can inform and advance the study of episodic memory.

One way researchers have been employing fMRI to help inform different theories of episodic memory is to image HC and the surrounding MTL cortex which have been identified to be critical for memory and to observe specific patterns in the neural responding. The underlying assumption tested by this endeavor is that MTL activation patterns, both in terms of neural response functions and the localization of activation, should show distinct differences for "remember" versus "know" responses if the dual-process theory holds true. On the other hand, if MTL activation increases in a continuous fashion across the two types of responses, researchers would take this as support that a single type of representation and process supports episodic memory function.

Indeed, the above endeavor has produced compelling evidence that subregions of MTL are preferentially sensitive to different aspects of episodic experience, and has helped advance a

componential view of episodic memory which has received wide support. In this way, cognitive neuroscience investigations have engendered strong evidence that episodic memory is supported by multiple types of information, and is more consistent with other models, such as the dual-process models, that also incorporate this characteristic. An example of a model that adopts such a componential view is the Binding of Items in Context (BIC) model**.** This model proposes a coherent account of the flow and processing of episodic information into MTL and details the resulting types of memory representations (Diana, Yonelinas, & Ranganath, 2007; Eichenbaum, Yonelinas, & Ranganath, 2007).

As put forward in the BIC model, episodic memory consists of item information ("what") processed in the perirhinal cortex (PRC) and context information ("where") processed in the parahippocampal cortex (PHC) that are bound together via relational processing in HC ("how"). The functional specialization of PRC and PHC invoked in this model was originally based on animal research (for review, see Burwell, 2006). Subsequently, functional neuroimaging studies in healthy humans have also yielded data showing dissociable neural sensitivity for item, context, and relational information in PRC, PHC, and HC respectively, to the same stimuli within an experiment (Staresina & Davachi, 2010; Staresina, Duncan, & Davachi, 2011; also see Chapter 2 for a more in-depth review of this literature).

Theories of Hippocampal Function in Episodic Memory

Given that multiple lines of evidence, from animal research, neuropsychological studies, and cognitive neuroscience, all point to the critical role of HC plays in episodic memory, gaining an understanding of the computations and representations supported by HC is therefore a logical and important avenue of research.

One theory of HC function that has been widely investigated is the spatial mapping or cognitive map theory. Inspired by findings in rodents that HC neurons have preferential spatial locations to which they consistently respond, this theory proposes that the nature of HC computations and representations are inherently spatial (Fallis, 2013; Nadel, 1991). Subsequent neuroimaging studies in human have indeed also found consistent HC activation to spatial information.

However, to find that HC is sensitive to spatial information does not exclude the possibility that HC may be critical to other types of information and mental processes, of which spatial information may be an instance. Most notably, a spatial account of HC function does not make contact with the well-established neuropsychological finding that HC is critical for memory. Moreover, impairments in memory from HC damage are not limited to the domain of space and have been demonstrated to occur in different modalities of stimuli, such as words and unnamable novel stimuli (see section below).

Taking into account the domain-general manner of memory impairment given HC damage, a prominent and alternative theory to HC function is the **relational memory theory** of HC function (Cohen & Eichenbaum, 1993; Eichenbaum & Cohen, 2001). This theory emphasizes the relational nature of the mental process and representations supported by the HC, differentiating it from the above-mentioned theories that propose HC involvement in a singular information modality (such as spatial information) or specific level of memory strength (such as in signal-detection models). As reviewed below, relational memory theory can arguably be the dominant and working theory of HC function, and is central to the understanding of episodic memory. Consequently, further clarifying the sensitivity of relational memory representation to different factors is the chief objective of this dissertation.

Properties of Relational Memory Representations

Under relational memory theory, memory representations supported by HC are proposed to have the following information properties—(1) the representation contains information on how multiple perceptually discrete elements, either of the same or of different modalities, and regardless of modality, are *related* or *bound* to each other; (2) the collection of relationships between encoded elements is arbitrary; (3) the relational representation can be flexibly utilized and expressed (Cohen et al., 1997; Eichenbaum & Cohen, 2001; Konkel & Cohen, 2009; Watson, Cohen, et al., 2013). An example of a relational memory representation with these properties would be one that supports an episodic memory for an event (e.g. a party) involving people, names, faces, objects, how they are related to each other (e.g. names to faces, people to gifts), under what particular situation or context (e.g. a birthday celebration), and at which location and at what time (e.g. the patio of a friend's house at 8pm last Monday). The relationships between all components of the event are arbitrary and unique to this birthday party, thus act to distinguish this representation from all other parties that might have involved the same set of people and location. The ability to imagine this event with alternative details (e.g. instead of the patio, imagining it taking place indoors) would be an example of a flexible expression of the information involved.

Support from Animal Research

The proposal that HC processing is modality-general but computationally and representationally specific to "relations" allows relational memory theory to speak to a wide range of experimental designs and findings. For example, as researchers have argued, spatial information is inherently relational in its composition. Therefore, spatial information is a subset

of the type inputs that require relational computation and representation supported by the HC , rather than being the nature of the memory representation itself (Cohen & Eichenbaum, 1991; Eichenbaum & Cohen, 2014; Howard & Eichenbaum, 2015; Schiller et al., 2015).

Evidence that HC is a domain-general, relational information processor not limited to spatial information has been demonstrated in a variety of studies. In rodents, HC pathway lesions have been found to impair learning of relational information that was not reliant on spatial information. For example, Eichenbaum, Fagan, & Mathews (1988) demonstrated that rats with lesions to an input pathway to HC were severely impaired in learning simultaneously presented pairs of odor cues (which required relational processing to learn the pair-wise associations), while learning was preserved when the cues are presented separately in the same location (which required the learning of item information). In this way, this study demonstrated an impairment in relational learning independent of item memory. Equally powerful support for the relational memory theory is found in studies of direct recording from rat HC neurons. Researchers have identified “time cells” in HC that show preferential firing to specific moments in *time*. In these experiments, HC neurons fire sequentially as modulated by the flow of time within the experiment (Kraus, Robinson, White, Eichenbaum, & Hasselmo, 2013; Kraus et al., 2015; Manns, Howard, & Eichenbaum, 2007). Addition studies further rule out the possibility that spatial information may have modulated the time-dependent HC findings. The same finding of “time cells” has been demonstrated in immobilized rats where temporal organization of the experiment was imparted by the presentation of odors and the animals were not required to move nor mentally plan for movement through space (Macdonald, Carrow, Place, & Eichenbaum, 2013).

Support from Human Research

In humans, there is also a large body of evidence that shows memory for relational information, regardless of information content—spatial, temporal, between items, or even features within an item, engages and critically relies on HC processing. There is converging evidence from neuropsychological studies with amnesic patients, functional neuroimaging studies (fMRI), as well as from specialized paradigms that record eye movement behavior as an implicit and additional measure of memory performance.

First, in terms of neuropsychological evidence, amnesic patients show impairment for a wide range of materials. In one study, amnesic patients were tested on recognition memory for spatial positions, temporal order, and the associative information of the triplet of unnamable pipe-shaped tori stimuli shown at study. Patients with damage limited to the HC proper showed severe impairments in all three types of recognition tests of relational information but had preserved (above chance) performance on item memory (discriminating an individual tori). Thus, this study provides strong support that HC function is domain-general but processing-specific to relational information (Konkel, Warren, Duff, Tranel, & Cohen, 2008). In another study that shows equally strong support of the relational nature of HC processing, amnesic patients were required to physically reconstruct object array of 2 to 5 items on a surface studied just seconds prior. It was found that amnesic patients overwhelmingly made an error of reversing the location assignments between pairs of objects. Such “swap errors” indicate a fundamental impairment in the ability to “bind” object-location relational information and provide strong support for the role of relational processing by HC (Watson, Voss, Warren, Tranel, & Cohen, 2013).

In studies of cognitively normal populations, HC neural activity has been shown to correlate with memory performance on tasks where relational memory must be utilized in order

to obtain correct task performance. For example, in a study by Hannula and Ranganath (2008), participants studied visual displays of objects occupying a grid. At test, participants were required to recognize images that correctly showed the studied configuration after a 90-degree rotation. Successful performance on the task required memory for the relative positions of the grid items to each other, and therefore, relational processing. It was found that HC activity during encoding predicted later recognition performance. Additionally, HC activation was greatest for test displays that preserved all studied item-location information as compared to trials with altered relational information, thus providing further evidence of HC sensitivity to relational information.

Current Investigation: Characterizing the Sensitivity of Relational Memory Representations to Different Factors in Episodic Memory

After the brief review of theories and models on episodic memory, we hope to have sufficiently highlighted that (1) the item versus relational information distinction is important to current investigations of episodic memory, and that (2) the study of relational memory representations is a crucial part of this endeavor.

With this in mind, this dissertation aims to contribute to the understanding of episodic memory by investigating the sensitivity of relational memory representations to factors that commonly accompany episodic experience. The overarching question is whether all types of relational memory representations are created equal, or whether the presence of repetition, negative emotion, and context information influences such representations, and in what manner. To this end, specific care taken in utilizing and designing novel paradigms that allow for the examination of relational memory independent of, or controlling for, item memory contributions.

Below, we briefly outline the three experiments reported in later chapters of this report and the central questions they address.

Study 1: Modulation of Relational Memory Representation by Repetition

The first study, as detailed in Chapter 2, investigated the effect of study repetition on MTL neural activity during retrieval of relational face-scene paired stimuli. The main goals of the study are—(1) to identify separable MTL subregions that are sensitive to item versus item-in-context relational information; (2) to seek novel evidence of HC activity modulating to strength of relational information independent of item information changes; (3) to manipulate item and relational information objectively, rather than rely on subjective assessments of memory confidence, via a novel paradigm informed by cognitive models of episodic memory, using spaced repetitions of item and item-in-context information at encoding.

To expand on the above –first, the paradigm allowed for modeling of neural activations associated with item information increases separately from those associated with context and relational information increases, while keeping the visual input constant between both conditions during the time of fMRI data acquisition. If results conform to previous proposed functional organization of the MTL, such as those outlined in the BIC model (Diana et al., 2007; Eichenbaum et al., 2007), we would expect to find sensitive of PRC to item information (face), PHC to context information (scene), and HC to relational information (face-scene pair).

Second, we hoped to find modulations of neural activity in these regions that correlate with the strength of information being represented. In particularly, if we could find graded HC activations that track changes in relational information, it would constitute a novel finding to this field of research.

While repetition-related neural activity at memory retrieval has been widely studied and established for item information in the PRC, few research studies have used fMRI to examine HC neural activity to memory of repeated stimuli. For the PRC, there is previous evidence that show *decreases* in neural activity with increased repetition of studied items – a phenomenon termed "repetition suppression" (Brozinsky, Yonelinas, Kroll, & Ranganath, 2005; Voss, Hauner, & Paller, 2009; Wang, Ranganath, & Yonelinas, 2014). In terms of HC, only a few experiments have examined repetition effects using fMRI. However, these studies have so far only used item stimuli (Manelis, Paynter, Wheeler, & Reder, 2013; Yassa & Stark, 2008) but not stimuli that involves experimentally defined relational binding. In contrast, our study employed arbitrarily paired face-scene stimuli that requires relational processing and have been demonstrated to elicit HC activity (Hannula & Ranganath, 2009). Therefore, our experiment was better poised to investigate repetition effects in HC.

Attempting to identify repetition modulated activity in HC is a significant endeavor, as it would provide a novel datum on HC involvement in episodic memory that the prior-reviewed theories and models would have to account for. Additionally, results of MTL subregion sensitivity to variations in item and relational information within the same study, would contribute evidence to the functional organization of the MTL.

Study 2: Modulation of Relational Memory Representation by Negative Emotion

The second study, detailed in Chapter 3, investigated the factor of negative emotion and its effects on relational memory representation. Participants studied faces paired with neutral or negative scene images and later performed a recognition test while undergoing eye tracking throughout the experiment.

Previous studies on the interaction of negative emotion and episodic memory have yielded contradictory results. This line of research was first inspired by reports of "flashbulb" memories of extraordinarily detailed and indelible remembrance of highly arousing, typically negative events (Christianson, 1992; Christianson, 1989). However, subsequent studies found contradictory effects for different elements within each memory episode, with some aspect of the memory being enhanced and others impaired. Some theories looking to account for the data adopt a spatial-attentional explanation, proposing central information enhancement and peripheral information impairment as the organizing factors of the observed effects (Christianson & Loftus, 1991; Kensinger, Garoff-Eaton, & Schacter, 2007). Yet other studies have attributed opposing results to differences in motivation or goal-orientation state (Kaplan, Damme, & Levine, 2012; Levine & Edelstein, 2010).

An additional explanation, we propose, is that enhancing or impairing effects of negative emotion on memory may depend on the nature of the memory processes and representations being probed–specifically, whether relational or item memory processing is involved. In other words, we believe that one should take into account theories of episodic memory processing when studying its interacting effects with emotion. To some extent, some studies have begun to adopt this approach by examining emotion modulation of memory via the item-source or item and context frameworks of episodic memory. However, these efforts have again yielded mixed findings (Madan, Fujiwara, Gerson, & Caplan, 2012; Pierce & Kensinger, 2011; Schmidt, Patnaik, & Kensinger, 2011). We propose that these contradicting results on the effects of emotion on item-source or item-context memory may reflect a mixture of underlying memory processes being taxed in these various studies. For example, some item-source information could be remembered using a more item-like, unitization processing (Diana, Yonelinas, & Ranganath,

2008) while others require relational processing. Greater care may be required to isolate the type of memory process being tested in a given study, in order for unambiguous effects of emotion on memory to emerge.

To this end, in Study 2, we employed a modified version of the face-scene relational eye-movement paradigm published by Hannula, Ryan, Tranel, and Cohen (2007) which directly tests relational memory while controlling for possible contributions from item information. Participants studied faces superimposed on scene of either neutral or negative valence, and were then tested for their recognition of the face-scene pairs by choosing the matching study face among 2 other equally studied lure faces. The novel hypothesis tested here is that emotion negatively affects *relational processing* rather than the content of the representation (item or context/source).

Additionally, this paradigm utilized eye tracking to provide an additional, implicit measure of memory performance that has been shown to be an especially sensitive measure of relational memory (Hannula et al., 2010). In terms of test time eye movements, previous studies using the original design (with neutral stimuli) have found greater of viewing to the face that correctly reinstates face-scene paired images than to lure faces (Hannula et al., 2007) and that this viewing pattern is predicted by HC activity (Hannula & Ranganath, 2009). Thus, by examining eye movements at the recognition phase of the experiment, we had an additional of index of possible changes to relational memory representation by the presence of negative emotion. In terms of study time eye movements, such data had yet to be reported with this particular paradigm and therefore the results collected were novel. The motivation for including eye data from the encoding phase were that (1) we could examine the distribution of overt attention during encoding, to discover, or to demonstrate the lack of, differences between the

neutral and negative conditions and (2) we could identify visual sampling patterns that predicted eventual recognition accuracy (subsequent memory effects in eye movements) and investigate whether these patterns interacted with emotional valence.

Lastly, this study also included a repetition condition, where half of all studied trials (in both neutral and negative conditions) were studied twice. This manipulation was included to better diagnose the influence of negative emotion induced attentional biases on relational processing. If negative emotion disrupts relational processing, we would not expect to see repetition benefitting (or rescuing) memory performance in the negative scene conditions. However, if negative emotion affects relational memory representations via changes in attention allocation during encoding, we would expect some recovery of relational memory performance for negative trials that had repeated study, compared to those without.

In summary, this study employed a sensitive and targeted test of relational processing, further aided by fine-grained data obtained through eye tracking, to investigate the effects of negative emotion on relational memory. Our hypothesis predicted negative emotion should have a detrimental effect on relational memory performance that is beyond potential attention distribution differences during sampling.

Study 3: Modulation of Relational Memory Representation by Context

The third study, detailed in chapter 4, investigated the factor of "context" information and its influence on relational memory representation. The study approached this topic by asking the question – what information properties determine which elements of an experience are processed as context and how does the presence of this property impact episodic memory for the event?

The idea of "context" is an essential construction in the study of episodic memory. It is the conceptualized as the information that differentiates recollection from a feeling of knowing, according to the dual-process theories of episodic memory (Eichenbaum et al., 1994; Rugg & Yonelinas, 2003; Yonelinas, 2002) or as the component information that is bound to item information in HC to support episodic memory in the BIC model (Diana et al., 2007; Eichenbaum et al., 2007).

Additionally, context information has significant influences on episodic memory performance. Maintaining the same context between encoding and retrieval leads to greater probability of recall (Godden et al., 1975; Rutherford, 2004; Staudigl & Hanslmayr, 2013) while changing the context from study to test can impair memory (Hayes, Baena, Truong, & Cabeza, 2010; Hayes, Nadel, & Ryan, 2007; Murnane, Phelps, & Malmberg, 1999).

Despite the frequent invocation of context and its established impact on behavior, there is limited understanding of the nature of its representation. In research, context has been operationalized as scene images (Duarte, Henson, & Graham, 2011; Hannula et al., 2007; Hayes et al., 2007), a single perceptual feature accompanying to-be-learned information, such as color (Staresina & Davachi, 2008; Tendolkar et al., 2008), screen location (Cansino & Trejo-Morales, 2008; Yu, Johnson, & Rugg, 2012), or a behavior task such as animacy and commonness (Kensinger & Schacter, 2006a; Ranganath et al., 2003) or gender and size judgments (DuBrow & Davachi, 2013).

In Study 3, we tested the hypothesis that context information, at its most fundamental, consists of a subset of elements in an experience that have the most *stable* or consistent interrelationships across multiple encounters involving them. For example, the context of an "office space" would likely contain office furniture and stationary amongst its many elements.

Furthermore, the relational information between these elements would likely be stable across experiences --the furniture always sit atop the floor, and the stationary distributed atop the furniture. The elements within the space that do not have such stable relationship, such as an office's occupants who are free to move around, are more item-like. If the same furniture and stationary were somehow separately stacked in different corners of a space, it may more likely constitute a "office supplies store" context than a working office space. In the same vein, we hypothesized that it is stability of the relational information between constituent items of an experience, rather than the identity of the items themselves, that determines what is processed as context information.

To test our hypothesis that the collection of elements with the greatest stability in their interrelationships becomes context-like, we devised a novel paradigm where *relational stability* is the only feature that differs between elements within each studied episode. The effects of relational stability as context was indexed by participants' recall memory performance. Eye-movement data was also recorded throughout the experiment to provide an additional and more sensitive implicit measure of memory.

Specifically, participants studied 2 pairs of object-object images pairs occupying 2 quadrants of the screen per study trial. Critically, a limited number of objects were repeatedly sampled in different combinations across the study trials. In this way, we mimicked the property of everyday events –that the same items can either be item or context information, what imparts more context-like properties is those with more stable relational information. We operationalized "context" as stable item-location relationships. As such, a subset of the object stimuli had stable locations on the screen. Whenever such stimuli were sampled to appear in any given study trial, it was presented in the same screen location. Such item-location stability would not be

immediately apparent to participants, as each study trial only sampled a subset of the stimuli. The stability property had to be integrated across multiple exposures. Item information, in this study, consisted of the remaining subset of stimuli that appeared in all possible screen locations and, therefore, ostensibly did not have any type of stability of information associated with them.

Success of context-like effects induced by relational stability was indexed via changes in memory performance. As it has been shown in rodent studies that context information provided an organizing structure for episodic memory representations (McKenzie et al., 2014), we hypothesized that successful context manipulation should aid memory recall. In this experiment this would manifest as increased accuracy or more structured reconstruction performance compared to conditions where no stable item-location information was present. In addition, by obtaining eye movements during task, we had an especially rich and sensitive measures of memory (as revealed in study 2) that may help reveal differences in the organization of the episodic memory between conditions with stability information versus those without.

CHAPTER 2: MODULATION OF MEDIAL TEMPORAL LOBE ACTIVITY BY OBJECTIVE ITEM AND RELATIONAL MEMORY STRENGTH VARIATIONS

Abstract

Most memory theories postulate that episodic memory traces contain both item and item-in-context information. In this study, we used fMRI to evaluate neural activation during recognition test phase in response to repetitions of item and context during encoding. Participants studied displays of faces (items) superimposed on scene images (contexts). To increment item information, face stimuli were presented on the screen 0, 1, or 2 times before they were paired once with their unique scene context. To increment item-in-context information, faces were repeated with their unique scene context 1, 2, or 3 times. During the test phase, participants were shown face-scene displays that were either intact from the study phase (old), never studied (new), or familiar faces and scenes taken from different study displays (rearranged). Differential effects of item and context repetitions were detected in recognition accuracy. Importantly, fMRI data revealed decreasing activation in the right parahippocampal cortex that tracked item repetitions at encoding, whereas bilateral hippocampus showed decreasing activation that tracked context repetitions at encoding. These findings demonstrate dissociated neural substrates in the medial temporal lobe that are differentially sensitive to repetitions of item and item-in-context information.

Introduction

Recognition memory supports the ability to identify previously experienced events encoded into episodic memory. A well-received proposal from recent investigations and theories of recognition is that episodic memory traces constitute of multiple streams of information specifically combined to represent complex events. Principally, the distinction is between that of *item, context,* and *item-in-context relational* information (Diana et al., 2007; Eichenbaum et al., 2007; Ranganath, 2010). While item information refers to features under attention and/or is the experimenter-defined subject of memory, context is defined as all other incidental features present during the encoding of an item (Mitchell & Johnson, 2009; Rudy, 2009). *Relational* information captures the combination of items in their contexts, and it specifies the associations formed between the item and the context features (Cohen & Eichenbaum, 1993; Cohen, Poldrack, & Eichenbaum, 1997; Eichenbaum & Cohen, 2001).

In this study, we independently varied *item* and *relational* information through repetitions of face-scene pairs at encoding by incrementing item strength, while holding the relational information constant, or incrementing relational strength, while holding the item information constant. We used fMRI at retrieval to detect neural activity that reflects *prior history* of the studied information, with the goal of identifying functional regions that are differentially sensitive to repetitions of item and relational information. Demonstrating a double dissociation of functional specialization in medial temporal lobe (MTL) regions within a single study would provide strong support for multi-stream account of episodic memory.

Behavioral Evidence of Item and Relational Information in Episodic Memory

The idea that episodic memory consists of the combination of multiple streams of information is well supported by behavioral studies and the theories they inspire. In single-item recognition tests, models assuming separate item (or the feeling of "knowing" or having "familiarity") and item-with-context (or the feeling of "remembering" or having "recollection") streams of information better predict patterns of recognition performance and their relationship to subjective assessments of confidence (Yonelinas, 2002) compared to single-stream information models; this is formalized by receiver operating characteristics (ROC) analyses (for a review, see Yonelinas & Parks, 2007). Studies on the list strength effect (LSE) also support the distinction between the item and context information (Malmberg & Shiffrin, 2005). The LSE refers to the phenomenon that strengthening some items in a list adversely affects recall of the remaining items on that list (e.g., Tulving & Hastie, 1972). Most importantly, whether or not the LSE is observed depends on the nature of the strengthening manipulation. Items strengthened via *distributed repetitions* at encoding produce the LSE, whereas items that receive additional study time or elaborate encoding do not. The nature of the interaction with various strengthening manipulations is interpreted in terms of differential accumulation of item and context features in the memory trace. Namely, the LSE is said to arise from retrieval competition of memory traces containing stronger context features, which accumulate with distributed repetitions, whereas the absence of the LSE is explained in terms of the strengthening of item features but not context features (Malmberg & Shiffrin, 2005). Thus, the distinction between the item and context information and the manner in which these two types of information accumulate as a result of repetition explains the LSE (for a review, see Malmberg, 2008).

Finally, theories with multi-stream assumptions extend to account for memory performance during *associative recognition,* which probes memory for relational information. In standard recognition tests, the participant makes a simple decision of whether a probe item is old or new. In contrast, associative recognition tests require more nuanced distinctions that decouple memory for items and memory for associations between the items. In such paradigms, stimuli are studied together (e.g. word-pairs, or face and scene combinations), and at test participants are tested on their memory for relational information such as whether a given face was presented with a certain scene, or whether two words were paired together during encoding. Models that posit multiple streams of information, such as one for "remember" or "recollected" responses and another for "familiar" or "know" responses better fit the observed memory performance and participants' subjective memory confidence on these tasks compared to models assuming single-stream information (for reviews, see Malmberg, 2008; Yonelinas, 2002). Taken together, behavioral studies and their inspired theories provide strong evidence for a multi-stream account of episodic memory representation.

Neural Evidence of Item or Relational Information in Episodic Memory

If episodic memories consist of multiple streams of information, evidence of such functional specialization should be observable via functional neuroimaging. Indeed, across different studies, subregions of the medial temporal lobe (MTL) attributed to memory function, were shown to be sensitive to different types of episodic information. For example, during encoding, the anterior parahippocampal cortex (ant. PHC) and more specifically the perirhinal cortex (PRC) show greater activity for subsequently recognized items than for subsequently forgotten items (Davachi, Mitchell, & Wagner, 2003; but see Gold et al., 2006), suggesting that

these regions are sensitive to the item information. Relational information, on the other hand, appears to rely critically on the involvement of the hippocampus (HC, Cohen & Eichenbaum, 1993; Eichenbaum & Cohen, 2001). For example, patients with hippocampal damage are severely impaired at recognizing objects in locations (Watson, Voss, et al., 2013), face and scene pairs (Hannula & Ranganath, 2009; Hannula et al., 2007), and temporal and spatial configurations (Konkel et al., 2008). Also, fMRI studies find greater HC engagement during successful encoding of relational information compared to encoding of item information (Davachi & Wagner, 2002). Retrieval activity in HC further predicts successful relational memory expressed through eye movements (Hannula & Ranganath, 2009) as well as explicit recall of relational information (Giovanello, Schnyer, & Verfaellie, 2004; Hannula, Libby, Yonelinas, & Ranganath, 2013; Slotnick, 2010).

Neural Repetition Suppression and Item and Relational Information

Additional evidence of functional specialization comes from neuroimaging studies that demonstrate how neural activity in a brain region modulates with repetitions in the probed information at the time of test. As mentioned previously, PRC region is implicated in the encoding of item information. Other studies have also shown that during retrieval, the PRC region was less active in response to previously encountered ("old") items compared to novel ("new") items (Henson, Cansino, Herron, Robb, & Rugg, 2003), as well as during correct recognition of old items relative to those incorrectly classified as new (Weis, Specht, Klaver, Tendolkar, & Willmes, 2004). The *reduction* in PRC neural activity for items with successful memory compared to those without is termed *repetition suppression*.

The phenomenon of repetition suppression was first established in animal studies, where neurons in primate visual cortex showed attenuated response to repeated visual stimuli compared to stimuli seen once (Desimone, 1996; Miller, Li, & Desimone, 1993). Studies in humans replicated these results and further demonstrated that repetition suppression distinguished between brain regions with selectivity to different types of information during viewing (Goh et al., 2004; Suzuki, Johnson, & Rugg, 2011). While repetition suppression was first demonstrated with visual stimuli, its utility in identifying the functional specificity of brain regions involved in long-term memory has also been demonstrated.

As indicated above, reductions in PRC activity during recognition testing for items that are successfully recognized versus those that are not indicates that PRC is sensitive to item repetition effects. Intriguingly, while previous studies have demonstrated repetition suppression effects in regions that are sensitive to item information, to the best of our knowledge, no studies have investigated the effects of repetition of *relational* information, especially in the HC, which is critically implicated in relational processing. It remains to be examined if the neural response in HC is sensitive to repetition of relational information, or whether HC neural activity remains constant across repetitions of relational information, indicating that once the relational information has been encoded, it does not modulate the activity in HC when repeatedly encountered.

We note that whereas several studies examined neural responses in multiple MTL regions within a single study, they primarily focused on the effects of repetitions of item information, but not relational information (for review, see Eichenbaum et al., 2007). Specifically, a majority of studies asked participants to provide subjective confidence ratings during recognition test, increasing ratings indicated increasing item strength, and the highest confidence rating presumed

to implicate relational memory). Hence, repetition suppression in MTL subregions that varied parametrically with different levels of confidence were interpreted to reflect sensitivity to item information, whereas subregions sensitive to relational information were expected to show neural activity that differentiates between familiarity and recollected responses. Indeed, this pattern of results has been demonstrated with recognition paradigms at encoding (Davachi, Mitchell, & Wagner, 2003; Ranganath et al., 2003) and at retrieval (Montaldi, Spencer, Roberts, & Mayes, 2006). However, to the best of our knowledge, no studies have examined activity in HC in response to objective manipulations of relational information, and previous fMRI studies have only shown the HC involvement for the highest confidence rating responses (i.e., all-or-none response, as opposed to a graded response in HC to varying amount of relational information).

Current Investigation

To summarize, the goal of this study is to manipulate item and relational information independently, using repetitions of pre-experimentally unfamiliar stimuli such as faces and scenes. In this manner, neural activity at test can only reflect differences driven by the prior episodic history of encoding. In addition, the choice of unfamiliar stimuli ensures that the neural response is uncontaminated by prior semantic knowledge of stimuli. Our goal is to examine neural activity in response to repetition in MTL subregions that are implicated in the processing of item information (ant. PHC region) and relational information (HC). Obtaining a double dissociation of functional regions that are differentially sensitive to item and relational information within the same study would provide strong support for multi-stream accounts of episodic memory. In addition, this is the first examination of neural response in HC in response to *varying levels of relational information* at encoding.

Methods

Participants

The study recruited 20 right-handed adults (ages 18-35; 8 females) from the University of Illinois at Urbana-Champaign community. Participants provided written informed consent according to the guidelines of the Institutional Review Board and received monetary compensation for their participation. Data from 4 participants were dropped from the analyses due to excessive motion or technical issues during MRI scanning. Results presented hereafter consist of data from 16 participants (10 male, 6 female).

Experimental Paradigm

The experiment consisted of 10 study-test blocks. Stimuli were 360 color-photographs of faces (Althoff et al., 1999) and 330 scenes (Walther, Caddigan, Fei-Fei, & Beck, 2009). Study displays involved faces centrally presented on a black background (constituting *item* information), or those faces centrally superimposed over a scene image, forming a face-scene pair (constituting *item-in-context relational* information). The critical manipulation of *item* versus *relational* repetitions was achieved by varying the number of times faces were repeated in isolation (i.e., against the black background) before they were presented as a face-scene pair, as well as varying the number of times face-scene pairs were repeated during encoding (see Figure 2.1 and Table 2.1 for details). Each face-scene pair was unique. No face was studied with multiple scenes or vice versa. These critical experimental conditions were intermixed within blocks. Trials within the study and test blocks were pseudo-randomized such that no more than three consecutive trials came from the same experimental condition.

Each study block contained 48 trials showing 1, 2, or 3 repetitions of 18 unique face-scene pairs. This included 3 *intact* face-scene pairs associated with each of the 5 experimental conditions along with 3 pairs later used for *rearranged* trials. Each study trial began with a 1000ms fixation cross, followed by the stimulus for 3000ms. During encoding, participants made subjective yes/no judgments on whether a given face seemed to fit in with the scene presented in the background. For trials where a face appeared alone against the black background, participants were instructed to respond "no". The subjective judgment data is not reported here as it was a task of non-interest, used to direct participants' attention to the study material.

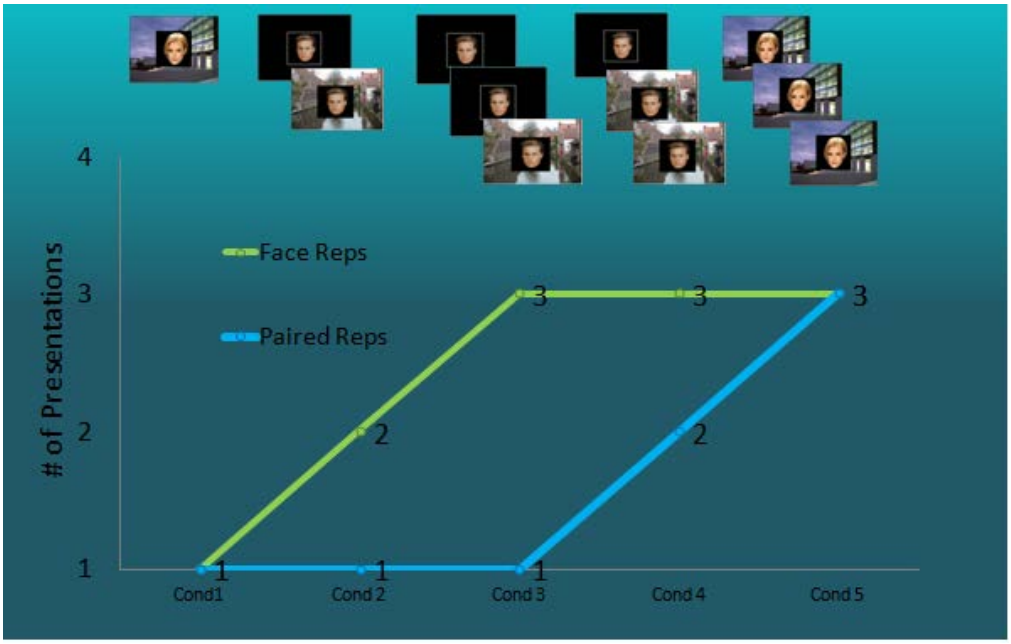


Figure 2.1: Experimental Conditions. To increase *item* repetitions while holding context information constant, conditions 1, 2 and 3 (top of the figure, going left to right) presented faces 1, 2, or 3 times, but only one time out of which were they paired with a scene. Item repetition is shown by the green line portion of the parallelogram. To increase *relational* information while holding item information constant, conditions 3, 4, and 5, presented faces three times and manipulated if faces were paired with their unique scenes 1, 2, or 3 times. Relational repetition is shown by the blue line portion of the parallelogram.

Participants performed the associative recognition test while undergoing fMRI imaging, and functional images were collected only during the test blocks. Each test block contained 36 test trials –15 *old* trials showing previously displayed face-scene pairs with varying degrees of *item* and *relational* study repetitions; 15 *new* trials with novel, never-studied, faces and scenes paired; 3 *rearranged* trials with pairs formed from previously studied faces and scenes from different study trials. Accuracy on *rearranged* trials required the encoding and utilization of *item-in-context relational* information such that novel pairings made from studied faces and scenes should be given a "new" response. The inclusion of *rearranged* trials therefore encouraged participants to attend to *relational* information in all trials. Finally, 3 trials of no interest containing only faces were used to ensure participants attended to face-alone stimuli during the study phase.

For the test trials, an instruction screen at the beginning of each block reminded participants of the response options, which consisted of a 5-point scale – 1: sure old, 2: maybe old, 3: don't know, 4: maybe new, 5: sure new. Participants were instructed to respond "old" only if they recognized the exact combination of face-scene pair (i.e. intact pairs) as studied in the preceding study block; any change in the presented pair at test from the ones studied should be given a "new" response (i.e. rearranged and new pairs). Each test trial began with a fixation cross lasting 1000ms, followed by a face-scene pair shown for 5000ms during which time participants made their response, followed by a fixation cross of variable length (see *Neuroimaging Procedures).*

Neuroimaging Procedures

Before undergoing the experiment in the fMRI scanning chamber, participants were given full instructions for the behavioral task as well as performed a practice block of study and test trials on a computer. The practice ensured participants fully understood the response criteria. Once situated in the MRI scanner, functional images were collected from participants during the test blocks. T1 structural images were collected at the point of the experiment, after 5 study-test blocks.

To ensure accurate timing of test trial onsets to image acquisition, each test trial was triggered by a scanner pulse signal. The variable duration of fixation cross at the end of test trials was in multiples of the image acquisition time (TR), ranging between 3 to 12 seconds. The variable fixation jittered the inter-trial interval at test, as a way to reduce the correlation between conditions of interest and to better maximize model estimation for a rapid event-related design used in this study.

Image Acquisition and Preprocessing

MRI data acquisition was performed on a 3T Siemens Trio Scanner with a standard whole-head coil. Functional data were acquired with gradient echo-planar image (EPI) pulse sequence (TR=3s, TE= 25ms, 2.5 x 2.5 x 3mm voxel size). To optimize signal coverage of the MTL, the 44 slices in each acquisition volume were aligned perpendicular to the long axis of the hippocampus of each participant. High-resolution T1-weighted (MP-RAGE) anatomical images were also collected.

Stimuli were back-projected onto a screen at the head of the scanner which was viewed through a mirror attached to the head-coil. Participants responded through a five-button

response-console that was placed beneath their right-palm and held in place by soft Velcro straps to ensure correct finger-button mapping throughout the scanning session.

FMRI Data Analysis

Preprocessing of the functional EPI images was performed using Statistical Parametric Mapping software (SPM 8. Wellcome Department of Imaging Neuroscience, London) and normalized to the Montreal Neurological Institute (MNI) EPI template. Spatial smoothing was applied with an 8 mm full-width at half-maximum (FWHM) isotropic Gaussian kernel. A high pass filter removed frequencies below 1/128 Hz that is likely to be noise.

Single-subject BOLD responses were analyzed using general linear models (GLM) specific to each subject's recognition memory performance. Test trials were sorted into correct versus incorrect trials. Correct responses for conditions 1 to 5 consisted of "old" responses (combining response ratings of 1 and 2). Correct responses for the repair and new conditions consisted of "new" responses (combining response ratings of 4 and 5). Correct trials were further grouped by their respective experimental conditions and their onset timing entered into the model as 8 events of interest—5 events for the *old* trials from experimental conditions 1 to 5; 1 event for *new* trials; 1 event for *rearranged* trials, and 1 event for face-only catch trials. All incorrect trials and "don't know" responses were modeled by 2 additional events. The decision to aggregate all incorrect and "don't know" trials across the conditions was based on the inference that participants likely did not fully attend to these trials during study, making the distinction between conditions less meaningful.

The modeled events were convolved with a canonical hemodynamic response function and their first-order temporal derivatives were entered as covariates into a GLM. Additional

covariates of non-interest included—6 motion parameters to capture minor movement during scanning; 10 nuisance regressors for the linear trend within each block and 1 regressor for the whole experiment.

Using the above-specified GLM, a set of least-squares parameter estimates (PE) was obtained for each participant. Contrasts of PE values were then performed to test for the significant contribution of specific experimental conditions (see *Contrasts of Interest*). Treating subjects as a random effect, the single-subject contrast PE's were entered into a second-level group analysis, where one sample *t* tests were conducted on the mean estimate for each voxel, testing them against zero.

Regions of Interest. FMRI data was analyzed using *a priori* defined anatomical regions of interest (ROI) within the MTL to identify memory regions that respond to successful recognition of memories with varying degree of *item* and *relational* repetitions (see Figure 2.2**)**. Based on extant evidence of functional specialization within MTL (Diana, Yonelinas, & Ranganath, 2007; Eichenbaum, Yonelinas, & Ranganath, 2007), we defined ROI's of the hippocampus (HC), anterior parahippocampal region (ant. PHC), which encompasses the perirhinal cortex (PRC), and posterior parahippocampal region, which is regarded as the parahippocampal cortex proper (post. PHC), separately in each hemisphere. The ROIs were manually defined on a high resolution MNI single subject brain volume (Tzourio-Mazoyer et al., 2002), following protocols established by Moore et al., (2014). Significant voxels within each ROI were determined given a small-volume corrected (SVC) familywise error rate of $p<0.05$. Visualization of results are at $p<.001$ uncorrected thresholds to show comprehensive results

affording comparison with other evidence in the literature (Poldrack et al., 2008), masked by the entire tested MTL volume.

Contrasts of Interest. FMRI contrasts were constructed to identify voxels whose activity was sensitive to patterns of *item* or *relational* repetitions. Specifically, to find repetition suppression effects, contrast weights of (2, 1, -1, -1, -1) identified voxels that were negatively correlated with *item* repetitions; contrast weights of (1, 1, 1, -1, -2) identified voxels that were negatively correlated with *relational* repetitions. For completeness, we also modeled positive correlations between neural activity and repetitions, applying contrast weights of (-2, -1, 1, 1, 1) to identify voxels positively correlated with *item* repetitions and contrast weights of (-1, -1, -1, 1, 2) to identify voxels positively correlated with *relational* repetitions.

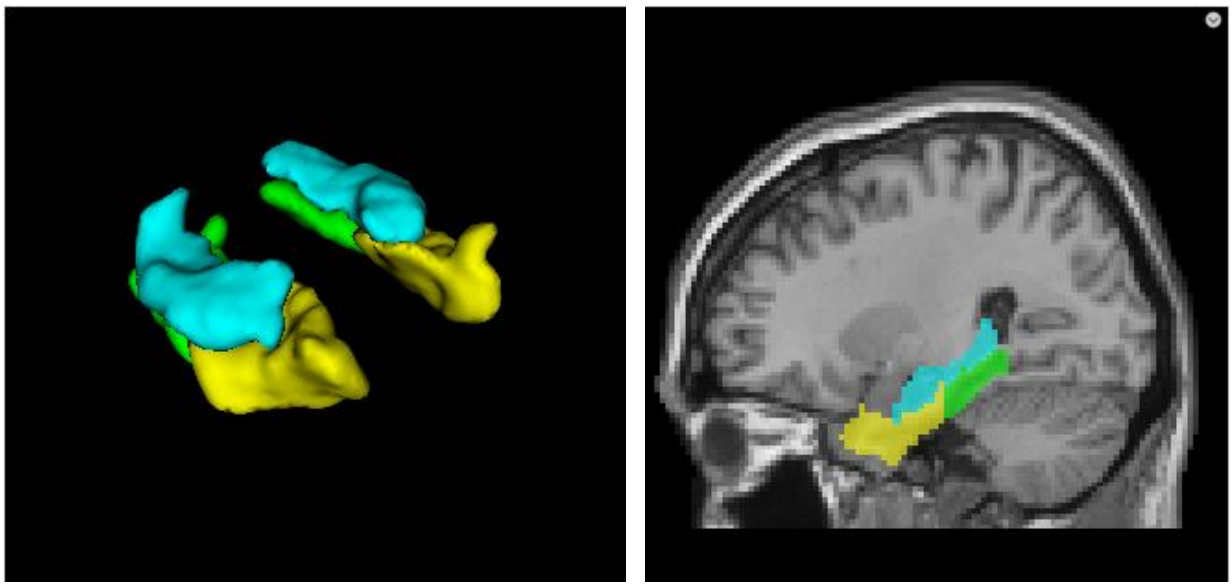


Figure 2.2: Views of the *a priori* defined regions of interest (ROI). **In blue:** left and right hippocampus (HC). **In yellow:** anterior parahippocampal cortex (Ant. PHC). **In green:** parahippocampal cortex proper (post. PHC).

Results

Behavioral Findings

Table 2.1 summarizes recognition performance, including hits (HT) and false alarms (FA), and discrimination accuracy (*d'*) across participants for each experimental condition of interest. Given there were two types of FA (from the *new* and *rearranged* trials), *d*' was calculated using each FA. The results were the same for both *d'* calculations, and to streamline, we report the statistics for the *d'* calculated using FA from the *new* trials. Repeated-measures analyses of variance (ANOVA) revealed that discrimination accuracy was significantly different across the 5 experimental conditions, F (4, 60) =11.257, $p < .001$ (MSE = 0.006, partial η^2 = 0.454). Post-hoc trend analysis further revealed a significant linear increase in *d'* from conditions 1 to 5, F (1,15) = 46.177, $p < .001$.

Condition	**Repetitions (Item, Context)**	**HT**	**FA (New)**	***d'***	**FA (*Rearranged*)**	***d'* (*Rearranged FA*)**
Cond1	**(1,1)**	0.69(0.05)	0.03(0.01)	2.52(0.21)	0.34(0.04)	1.01(0.22)
Cond2	**(2,1)**	0.71(0.05)	:	2.67(0.24)	:	1.15(0.25)
Cond3	**(3,1)**	0.74(0.05)	:	2.72(0.22)	:	1.20(0.22)
Cond4	**(3,2)**	0.80(0.05)	:	2.99(0.23)	:	1.48(0.23)
Cond5	**(3,3)**	0.86(0.04)	:	3.18(0.21)	:	1.66(0.22)

Table 2.1: Hits (HT) and false alarms (FA) and discrimination accuracy (d') across five experimental conditions.

FMRI Results

To identify neural activity within memory regions whose activation tracked the pattern of *item* or *relational* repetition changes during correct recognition, contrast weights were specified for PE's across conditions 1 to 5 and applied to voxels within the ROI's. All reported p-values are family-wise-error rate corrected within each ROI (FWE-svc), at the peak voxel for each activation cluster reported in MNI coordinates.

Item Repetition Variations. To model for repetition suppression (i.e., decrease in neural response) to increased item repetitions, a contrast of (2, 1, -1, -1, -1) was applied to mean PE's across conditions 1 to 5. Significant item repetition suppression effect was found in the right posterior PHC (39, -34, -14, p=0.015 FWE-svc, see Figure 2.3). Furthermore, neural responses in this cluster were dissociated from relational information; they did not significantly match contrasts that modeled variations in relational repetitions.

For completeness, we also applied a contrast modeling increases in neural response to increases in item repetitions (-2, -1, 1, 1, 1). This contrast would identify significant clusters within the MTL that positively correlated with the strength of item information. No above-threshold clusters were identified in any of the ROI's.

Taken together, we identified an MTL region (right posterior PHC) that is uniquely sensitive to item repetitions but not relational repetitions. This sensitivity was manifested as decreasing neural activity to increasing *item* repetitions, thus replicating the phenomenon of repetition suppression observed in other studies (Grill-Spector, Henson, & Martin, 2006; Heusser, Awipi, & Davachi, 2013).

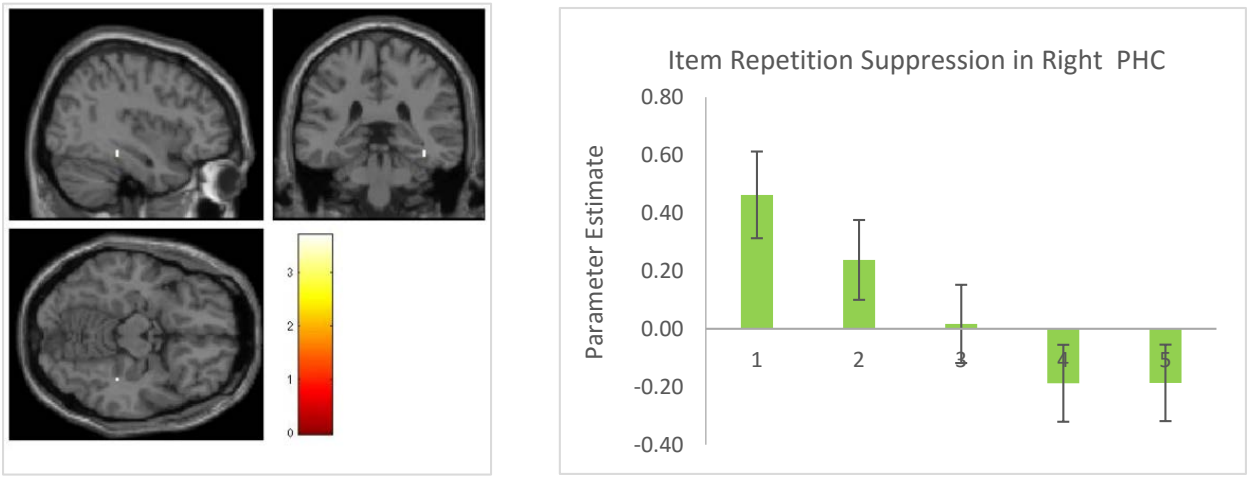


Figure 2.3: Item Repetition Suppression. Parametrically decreasing activation to increasing item study history in posterior right PHC (39, -34, -14, p=.015 FWE-svc). Activation bar graph extracted from significant voxel, for the purpose visualization only (not tested again for statistical significance). Bars are standard errors. Activation baseline is normalized across the whole experiment and should not be interpreted.

Relational Repetition Variations. To model for repetition suppression to increased *relational* repetitions, a contrast of (1, 1, 1, -1, -2) was applied to mean PE's across conditions 1 to 5. Significant activations were identified in the bilateral HC (18, -28, -8, p=0.019 FWE-svc; -21, -34, 1, p=0.032 FWE-svc) and the right middle PHC (18, -31, 8, p=0.007 FWE-svc; Figure 2.4). Furthermore, these supra-threshold clusters identified with the relational contrast were not statistically significant for any item variation contrasts.

For completeness, we also applied a contrast modeling increases in neural response to increases in relational repetitions (-1, -1, -1, 1, 2). This contrast would identify significant clusters within the MTL that positively correlated with the strength of relational information. No above-threshold clusters were identified in any of the ROI's.

Taken together, we identified clusters in the bilateral HC and right middle PHC that are uniquely sensitive to relational repetitions but not item repetitions. This sensitivity was

manifested as a decreasing neural activity to increasing *relational* repetitions. To our knowledge, this constitutes a novel demonstration of repetition suppression effects to variations in long-term relational episodic information, especially in the HC.

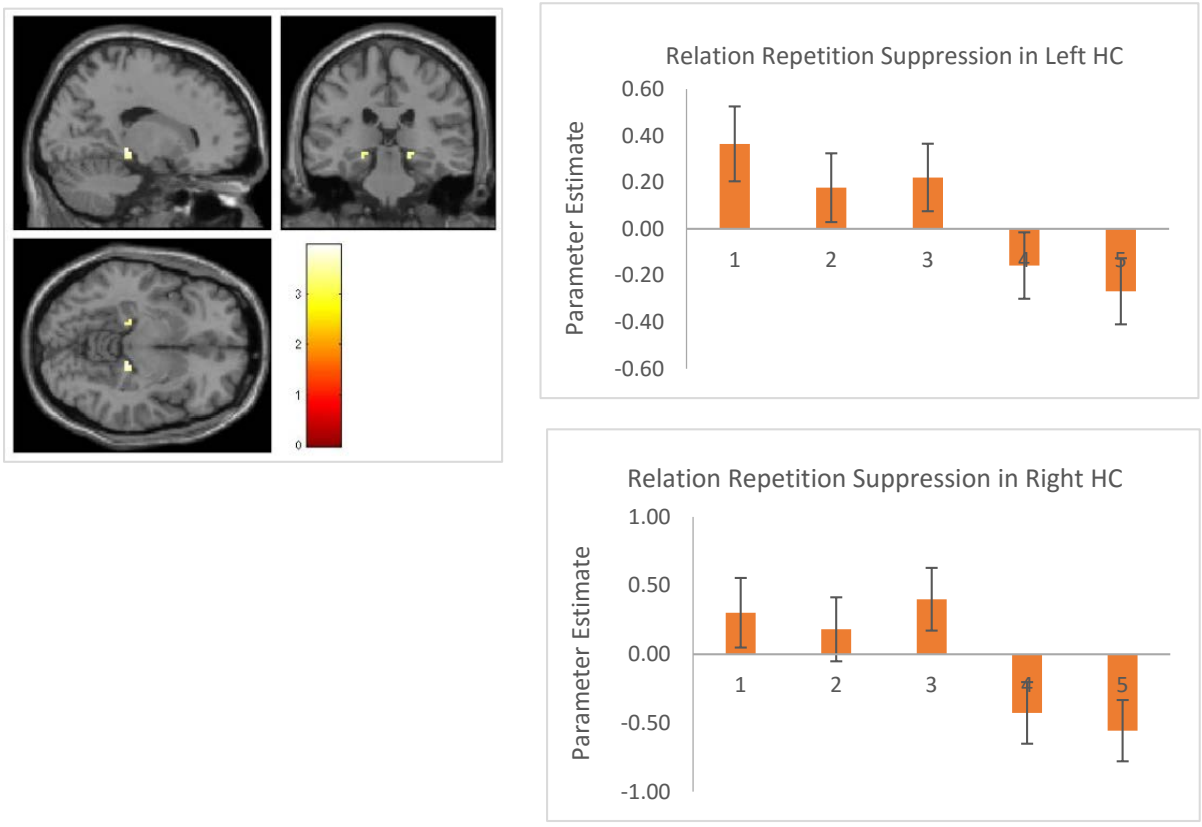


Figure 2.4; Item-in-context Repetition Suppression. Parametrically decreasing activation with increasing relational study history in the left and right HC (-21, -34, -1, p=0.032 FWE-svc; 18, -28, -8; p=-0.019, FWE-svc; pictured above). Activation bar graph extracted from significant voxel, for the purpose visualization only (not tested again for statistical significance). Bars are standard errors. Activation baseline is normalized across the whole experiment and should not be interpreted.

Discussion

In this report, we experimentally manipulated memory for *item* and *item-in-context relational* information by varying the repetitions of stimuli presented at study time. We sought evidence that distributed repetitions can advance each of these streams of information separately. Consequently, we also sought to see dissociations in the neural response to *item* versus *relational* information. Results from behavior outcomes and fMRI data show support for these hypotheses. We discuss each in turn.

Behavioral Findings

Participants were significantly more accurate in recognizing studied face-scene pairs that had received increasing repetitions during encoding. This suggests that the manipulation of stimulus repetition during encoding was effective and influenced memory. Increased accuracy across the five experimental conditions further suggests that the underlying memory representations had varying memory strengths in these conditions. This finding accords with numerous studies that manipulate repetition and observe positive effects on recognition memory, either via reduced false memory to word lists (Benjamin, 2001), better recognition of relational word pairs (Light, Patterson, Chung, & Healy, 2004), or better continuous recognition (Johnson, Muftuler, & Rugg, 2008; Suzuki et al., 2011).

In terms of the relative contribution of item versus relational information to recognition performance, we note that accuracy significantly increased in a linear manner across the 5 *old* conditions. This pattern suggests a combined effect of item and relational information towards recognition accuracy. In conditions 3, 4, and 5, where item information was constant and relational information increased, the increase in accuracy can be attributed to an increase in the

relational information. In conditions 1, 2, and 3, where item information increased but relational information was held constant, the increasing accuracy is driven by the increasing strength of the item information.

FMRI Findings

We identified neural response differences at retrieval that tracked study repetitions for item and relational information both within the ROIs. It is important to note that stimuli presented during the test phase were identical in stimulus category and layout, across all experimental conditions. Therefore, systematic differences revealed by the repetition-dependent contrasts should be attributable to the study-time properties, such as varying amounts of item and relational information.

Item Strength Variation. Decreased activation was found in the right posterior parahippocampal cortex to increases in studied item repetitions. This conforms to the phenomenon of repetition suppression, namely the decrease of neural activity to greater information, well established in the literature (Desimone, 1996; Grill-Spector & Malach, 2001).

With respect to item memory, specifically, repetition suppression has typically been observed in the PRC, a region hypothesized for item information processing (for review, see Diana, Yonelinas, & Ranganath, 2007; Eichenbaum, Yonelinas, & Ranganath, 2007). Repetition suppression in the PRC has been shown to be sensitive to increased item familiarity, (Henson et al., 2003; Tendolkar et al., 2008; Weis, Specht, Klaver, Tendolkar, & Willmes, 2004), as well as greater perceived item memory strength defined as differences between remember/know judgments (Gonsalves, Kahn, Curran, Norman, & Wagner, 2005).

The locus of the PHC activation identified in the present study, however, appears more posterior than would be expected based on the anatomical location of the PRC, which is in the anterior portion of PHC. Furthermore, few studies of MTL function implicate PHC in item memory processing. Thus, the current PHC finding may not speak to item memory strength processing per se, as was one of the original motivations for the current study design.

Alternatively, there are reported studies of decreases in PHC activity for increased memory strength, to which the present findings are relevant. Comparing responses from remember/know recognition judgments, Eldridge, Engel, Zeineh, Bookheimer, and Knowlton (2005) found greater PHC deactivation to trials with correct memory performance compared to trials without task-relevant memory (i.e. incorrect and correct rejection trials). Similarly, in the Gonsalves et al. (2005) study, a posterior PHC region was identified to show repetition suppression for increased item strength.

Relational Strength Variation. Significant repetition suppression of neural signals was identified in the left and right hippocampus, which tracked changes in study time of paired face-scene repetitions. The finding of graded HC activation to repetitions in stimulus study history is significant and has not been observed using designs with (1) objective methods of defining memory strength, (2) blocked study-then-test design with significant time in between the studied repetitions and time of fMRI data acquisition at recognition, and (3) a recognition test that encourages relational processing, such as utilized in the current study.

Observations of *decreasing* HC activation to increases in memory strength have only been reported in a few studies employing a continuous recognition paradigm (Johnson et al., 2008; Rugg et al., 2012; Suzuki et al., 2011). Data from these studies also show graded HC

activity to different number of stimulus repetition, providing corroborating evidence to findings of the current study. The present study, to our knowledge, is novel in its contribution of finding variations to relational information based on previous viewing history.

The inverse relationship between relational memory strength and HC activity observed here may be an instance of HC sensitivity to novelty detection and processing. Previous studies have found greater HC engagement for stimuli that are less familiar (Knight, 1996; Kumaran & Maguire, 2007; Nyberg, 2005). Continuous recognition studies also suggest evidence that greater HC activation during memory retrieval is related to the "amount" of information recalled, rather than a specific process or memory strength (Rugg et al., 2012). The current study further contributes this area of research by demonstrating HC response decreases with the experimentally defined amount of relational information formed from a prior encoded experience.

General conclusion. The current experiment identified separable MTL memory subregions that show dissociated neural responses to changes in item versus relational information, providing support for the multi-stream account of episodic memory. The finding of HC graded repetition suppression to parametric increases in relational information is a novel characterization of the neural response to relational information that has not been demonstrated in previous research.

CHAPTER 3: MODULATION OF RELATIONAL MEMORY BY NEGATIVE EMOTION

Abstract

Emotion is a ubiquitous part of everyday experiences and the memories formed from them. Much research centers on how emotion-induced attention biases may differentially impact memory for component parts of an event (such as central item versus peripheral information). Critically, studies have yet to query the possibility that emotion can act on specific memory processes, such as relational binding utilized to represent complex events with multiple elements, to influence memory. The current study examined the effects of negative emotional on relational memory for face-scene pairs. A repetition manipulation was included to examine the effects of emotion on memory after possible attention differences were given the opportunity to be equalized by repeated viewing. Eye movements were monitored throughout encoding and retrieval. Behavioral results showed a subtle impairing effect of negative emotion on behavior manifested as slower time to correctly respond while accuracy did not differ between negative and neutral conditions. More nuanced eye movement data revealed differences in encoding viewing of negative stimuli that changed across repetitions which did not affect memory accuracy. Thus, negative emotion may affect overt attention allocation without direct impact on relational memory performance. Overall, results show that negative emotion modulates relational processing in subtle ways, as manifested in differential encoding sampling patterns and slower response times under conditions of preserved relational memory.

Introduction

In the study of human memory function, research has uncovered emotional affect as a key factor that influences memory performance. Emotional stimuli or events have been demonstrated to either impair or enhance the ability to remember, with the deciding factors not conclusively identified. In eye-witness testimonies of highly charged, traumatic events, memory impairment manifests as a narrowing of attentional focus on certain elements of the experience, such the threatening weapon directed at the victim, at the cost of memory for other aspects of the event, such as the perpetrator's face. This phenomenon is known as the "weapon focus" effect (Loftus, Loftus, & Messo, 1987). At the same time, memory enhancements occur in the form of extraordinarily vivid and detailed recollection on the aspects of the event that are remembered (Kensinger & Schacter, 2006).

Researchers have devised various experimental designs to systematically investigate which factors lead to impairments and which to enhancements of memory by emotion. The results have not been conclusive but some patterns have emerged (for review, see Chiu, Dolcos, Gonsalves, & Cohen, 2013). First, emotional stimuli consistently lead to better remembering when there is low competition or need for selection for what is to be remembered within an event. This is the case when emotional items (such as objects, pictures, or words) are singly presented. In these instances, memory for items with emotional value (whether positive or negative) is superior to those items that are neutral in affect. Second, the effects of emotion are less clear when multiple elements are in an event, or when the binding of multiple elements or components is required for memory. On the one hand, stimuli with either positive or negative affect have been found to enhance memory for the source information, or circumstances, under which items are encoded. For example, when asked to recall the colors associated with previous

studied words, participants are more accurate in recalling the originally studied print color of positive or negative words compared to the color source of neutral words (Doerksen & Shimamura, 2001). Similar enhancements by emotion have been found for source memory in other stimulus modalities, such as the screen location of emotional objects/pictures (Mather & Nesmith, 2008). On the other hand, some experiments involving the binding of multiple components find worse memory performance for trials with negative affect compared to neutral trials. This detrimental effect of emotion has been observed in studies using either words or pictures associated to information across the domains of space (screen location), time (order of presentation), and other items (associated objects and pictures) (Bisby & Burgess, 2014; Madan, Lau, Caplan, & Fujiwara, 2009; Pierce & Kensinger, 2011).

Determining which factors lead to a detriment or enhancement in the remembering of emotional events with multiple components is important, as everyday experiences rarely consist of the encoding of Single items. Most real-world events are complex events with multiple components of information that require associating or binding together in a consistent and meaningful manner, so as to form coherent and retrievable memories. In a robbery scenario, while the threatening weapon may be of greatest emotional significance, other aspects of the event—such as time, location, physical appearances of the perpetrator, the presence of other people, all set the stage and form a context in which the robbery is situated. An understanding of how memory would function in such complex settings would be highly beneficial. This knowledge could inform the types of information that could be expected from eye witness testimonies, help formulate strategies that maximize memory efficacy during emotional events, and further our understanding of how memory processes are implemented in the brain, in terms of possible subprocesses or components.

Theories on what may explain the discrepant results of the effect of emotion on multi-element events have been generated through research. A prominent explanation posits a tradeoff in memory between central and peripheral aspects of an experience (Kensinger et al., 2007). Information central to an event is defined as that which imparts meaning or emotional significance to an experience. All other concurrent information in the event, often collectively referred to as context, consequently becomes peripheral. A tradeoff occurs in that central elements have enhanced remembering while peripheral elements are remembered less well compared analogous information in neutral events (Pourtois, Schettino, & Vuilleumier, 2013; Riggs, McQuiggan, Anderson, & Ryan, 2010; Riggs, McQuiggan, Farb, Anderson, & Ryan, 2011; Talmi, Schimmack, Paterson, & Moscovitch, 2007).

The mechanism put forward to explain the central-peripheral tradeoff is the attentional biasing effect of emotion. Attention is argued to be prioritized towards central (visually or conceptually) elements of negative events. This attention-narrowing effect of emotion is supported by behavioral reports of "weapon focus" (Loftus et al., 1987) or "tunnel memory" that is attributable to limited recall of contextual information (Safer, Christianson, Autry, & Karin, 1998). Other studies have also directly demonstrated attention bias to negative emotional stimuli, such as shorter visual search times for threatening stimuli among neutral ones (Ohman, Flykt, & Esteves, 2001), faster detection of dot probes occupying the same spatial location as emotional stimuli as compared to the opposite location (Koster, Crombez, Verschuere, & De Houwer, 2004), as well as the preferential capture of attention by faces with negative expressions compared to those that are neutral (Vuilleumier & Pourtois, 2007). In sum, multiple behavioral studies support the idea that emotion leads to prioritized attention.

Although there is support for differential attention allocation by negative emotion as an explanation for some of the effects of emotion on memory, such an account does not preclude the possibility that affective stimuli can affect memory performance independently of attention. Indeed, several studies have highlighted the possibility of non-attention based factors contributing to the enhancing and impairing effects of emotion. For example, Mickley, Steinmetz, Waring, & Kensinger (2013) found that the degree of attention narrowing on central elements of emotional events was not affected by divided attention manipulations. Yet other studies also provided support for a non-attention based account of emotional influence on memory by utilizing eye movement monitoring as an additional, nuanced and direct way of indexing the allocation of overt attention. For example, Christianson & Loftus (1991a) constrained analyses to stimuli that received equal amounts of overt attention, as indexed by the same number of eye movement fixations. Despite controlling for overt attention deployment, enhanced memory for central elements of emotional trials was still observed. Similarly, Riggs, McQuiggan, Farb, Anderson, & Ryan (2011) showed through mediation analysis that decreased number of fixations to peripheral elements compared to central aspects of emotional trials did not fully account for memory performance in their study. Thus, even though emotional stimuli do affect attention allocation during encoding, multiple studies suggest the existence of non-attentional factors that may contribute to enhancement or impairment of memory of emotional events.

One factor proposed to influence emotional memory beyond attention allocation is the modulation hypothesis. Initially inspired by animal studies (McGaugh, Cahill, & Roozendaal, 1996), the modulation hypothesis speaks to changes in memory processing due to neuromodulatory influences from the amygdala on memory processing regions in the medial

temporal lobes (MTL), such as the hippocampus. The amygdala is a region critical for emotion processing. Functional MRI studies find greater amygdala activation related to successfully remembered emotional items during encoding and retrieval (Dolcos, LaBar, & Cabeza, 2004; Hamann, Ely, Grafton, & Kilts, 1999; Kensinger, Addis, & Atapattu, 2011; McGaugh et al., 1996; Ritchey, Dolcos, & Cabeza, 2008). More importantly, increased activation in emotion processing regions is correlated with increased activation in the MTL for successfully remembered emotional events (Dolcos et al., 2004). Additionally, Fastenrath et al. (2014) used dynamic causal modeling to examine activity in the amygdala and hippocampus during encoding, to gain better understanding of the direction of agency between the emotion and memory regions. Modeling results supported a bidirectional influence between amygdala and hippocampus for the successful encoding of positive and negative pictures, with the amygdala influence on hippocampus being on a larger magnitude than vice versa. In sum, brain imaging studies in humans have found good support of mutual influences between the amygdala and hippocampus regions that could be indexing memory-enhancing modulatory influences of emotion on memory.

As a non-attention based explanation, the modulation hypothesis provides an account for memory benefits by emotional arousal that is in addition to influences of overt attention allocation. However, the modulation hypothesis only addresses instances of enhancements in memory performance. As reviewed earlier, the effects of emotion on memory beyond the central item, such as memory for the relationships between peripheral information to the item or between multiple elements within an event, are unclear. Emotion can either impair or enhance memory performance in these instances (Bisby & Burgess, 2014). Thus, there remains the unaddressed issue that there are emotional influences on memory not accounted for by either

attention bias nor the modulation hypotheses—namely, the impairing effect emotion can have on memory for relationships in an emotional event.

To address the outstanding question identified in the above reviewed literature, the current study investigated the effect of emotion on memory for binding and relationships within events, above and beyond attentional influences. Specifically, we hypothesized that the type of memory representation being queried is an additional factor that contributes to whether an enhancing or impairing effect would be observed on memory in the presence of emotion. We reasoned that, just as parcellation of emotional inputs into central versus peripheral items by attention can explain a portion of the opposing findings of the effects of emotion on memory, the type of memory representation being taxed could also account for opposing memory outcomes. Specifically, we proposed that emotion might negatively impact relational processing but not item memory. Such impairing effects of negative emotion on relational memory processing would be consistent with the observation that patients with post-traumatic stress disorder show disorganization in their memory (Dolcos, 2013).

Given our hypothesis, the current experiment was designed with four particular characteristics to better investigate the effects of negative emotion on relational memory. First, we adopted a relational memory paradigm involving face-scene pairs that has been established as an especially sensitive test of memory for relations or bindings (Hannula et al., 2007). In brief, the paradigm requires participants to correctly recognize face-scene paired information amongst lures that are also studied and equal in their degree of item memory. Accurate relational memory for which face is bound to which scene is specifically required for accurate performance on this task.

Second, we recorded eye movements during the retrieval phase, as an additional measure of relational memory. Eye movements, especially in conjunction with the experimental paradigm adopted in the current study, have been shown to be a sensitive index of relational memory (Hannula & Ranganath, 2009; Hannula et al., 2007). Thus, recording eye movements at test provided an opportunity for us to examine changes in relational memory expression that may not be detectable via overt memory accuracy.

Third, we also recorded eye movements during the study phase. This data would be novel with respect to the current paradigm and has not been previously reported. Our rationale for doing so was two-fold. For one, as reviewed earlier, study time eye movements provide a direct measure of overt attention. Thus, data from this period could help identify effects of emotion on relational memory that are mediated by differential attention allocation. For the other, per other memory paradigms with encoding measures, we could sort study time data by later memory accuracy, thus uncovering patterns of looking at study that was correlated with later successful memory.

Lastly, a repetition manipulation was incorporated, where half of the trials (from both negative and neutral valences) were presented twice during study, while the remaining half of the trials were presented only once. The inclusion of repetition allowed us to dissociate between an attentional account and our hypothesized modulation of relational memory account of the effects of negative emotion on relational memory. Specifically, the presence or absence of an interaction between emotion and repetition should shed light on this question. On the one hand, if attention allocation played a role in the current paradigm, second exposures to the same stimuli should offer chances at more even sampling of the presented display. In turn, we would expect repetition to attenuate the memory impairing effects of the negative stimuli, and this would be

manifested as recovered memory performance on the repeated negative trials compared to Single negative trials. On the other hand, if the influence of emotion on memory was a specific disruption of relational memory, we would expect minimal benefits of repetition for negative emotion trials. In turn, we would expect no difference between memory for Single and repeated negative trials. Last, if both of these factors played a role in the memory outcome, we would expect to find partial recovery of memory performance for repeated negative trials compared to Single negative trials but the extent of the improvement in performance would be less than that for repeated neutral trials compared to Single neutral trials.

In sum, we devised the current experiment with specific manipulations of emotion and repetition to provide insight into the relative degree of influence imparted by attention distribution versus our hypothesized disruption of relational memory by negative emotion. We expected the addition of eye-movement monitoring during study and test phases to further help tease apart the relative contributions of the two types of influences emotion may have on memory.

Method

Participants

Twenty-seven people from the University of Illinois community were recruited and compensated their participation in this study. Data from 21 participants were included in all following analyses (6 male; age M= 21, SD=3.0). Five participants were rejected due to poor behavioral performance (at chance accuracy) suggesting failure to comply with task demands and 1 participant's data was rejected due to data-logging errors.

Stimuli

Experiment utilized colored photographs of faces and scenes. The face images (144 male, 144 female) were obtained from a database previously used in Althoff & Cohen (1999). Photographs of scenes (144 neutral, 144 negative emotional) were taken from the International Affective Picture Systems database (Lang, Bradley, & Cuthbert, 1999), and grouped based on their normative valence ratings (on a 9 point scale, 1= unhappy, 9 = happy). Neutral images were selected to have valence ratings between 4.2 and 6.2 (M = 5.33, SD = .49); negative images were selected to have valence ratings between 4.07 and 1.31 (M = 2.77, SD =.67). We acknowledge that the upper bound of the valence ratings of negative images chosen for the current study was higher than would be used in most studies; the number of stimuli required for the current design necessitated this selection. A paired t test of the mean valence values of each emotion categories confirmed that they were statistically different, t (143) = -15.91, $p < .001$. Additionally, images were selected such that mean arousal ratings were similar in each neutral and negative block. Face images were 480 by 480 pixels and the scene images were 1280 by 1024 pixels, corresponding to the full resolution of the display monitor. Additionally, eye-tracking throughout the experiment was conducted with the Eyelink 1000 system. A desk-mounted chin rest was used to minimized head movement through out and improve the quality of eye-movement recordings.

Design

Experiment used a 3-face-scene relational memory paradigm as used in Hannula, Ryan, Tranel, & Cohen (2007). Each study trial consisted of a face centrally superimposed on a scene, forming a face-scene pair. After studying all the face-scene pairs within one block, participants were presented a series of test trials. In each test trial, a scene image was shown, followed by 3

superimposed faces, all previously seen in the study phase and therefore equally familiar. Participants were required to choose the face ("target face") that was paired with the scene during study from the other 2 lures ("familiar lures").

The current experiment had 4 conditions that differed on 2 stimulus dimensions: study repetition (Single or Repeated) and emotion (Neutral or Negative). In other words, trials could either be studied once (Single) or twice (Repeated), and the emotion of the scenes could either be natural or negative. Trials were organized such that study repetition was manipulated within each block and emotion was manipulated between blocks.

The experiment had 3 neutral blocks and 3 negative blocks that were presented in an alternating manner; the emotion of the scenes for the face-scene pairs varied across the blocks. Within each block, 24 face-scene pairs were studied once (Single) and 24 face-scene pairs were studied twice (Repeated), making up 72 study trials per block. Half of the faces in the study trials were male, half were female. To ensure comparable mean lapsed times between the first and second exposure to the Repeated trials, the first instances of the 24 Repeated pairs were presented during the first half (36 trials) of the study phase along with 12 Single trials; the second instances were presented during the second half (the latter 36 trials) of each study phase along with the another 12 Single trials. Sixteen test trials followed the study trials, with 8 trials for the Single and 8 trials for the Repeated condition intermixed in a pseudorandom manner, such that no more than 3 consecutive trials could be from the same repetition conditions. The 2 lure faces used in each test trial were always taken from study trials with the same number of repetitions and were of the same gender.

Procedure

Prior to the start of each study, experimenters explained the format of the task to each participant as well as positioned the participants appropriately in front of the eye tracker, with aid from the chinrest, to conduct a 9-point eye-movement calibration. Each study trial consisted of a fixation cross presented for 2000 ms, a preview of the scene image for 2000 ms, followed by the paired-presentation of a face centrally superimposed on the scene for 4000 ms. Participants were instructed to keep in mind how well they feel each face matched its background scene. Each test trial consisted of a fixation cross presented for 2000 ms, a preview of a scene image for 2000 ms, followed by the 6000 ms of the critical test display of 3 faces superimposed over the scene (see Figure 3.1). Participants responded via 3 buttons on a keyboard corresponding to face locations 1, 2, and 3 during the 3-face display. Eye-movements were recorded throughout both study and test phases of each block.

In terms of counterbalancing, four versions of the experiment were constructed and administered during data collection in order to achieve the following criteria. First, the pairing of

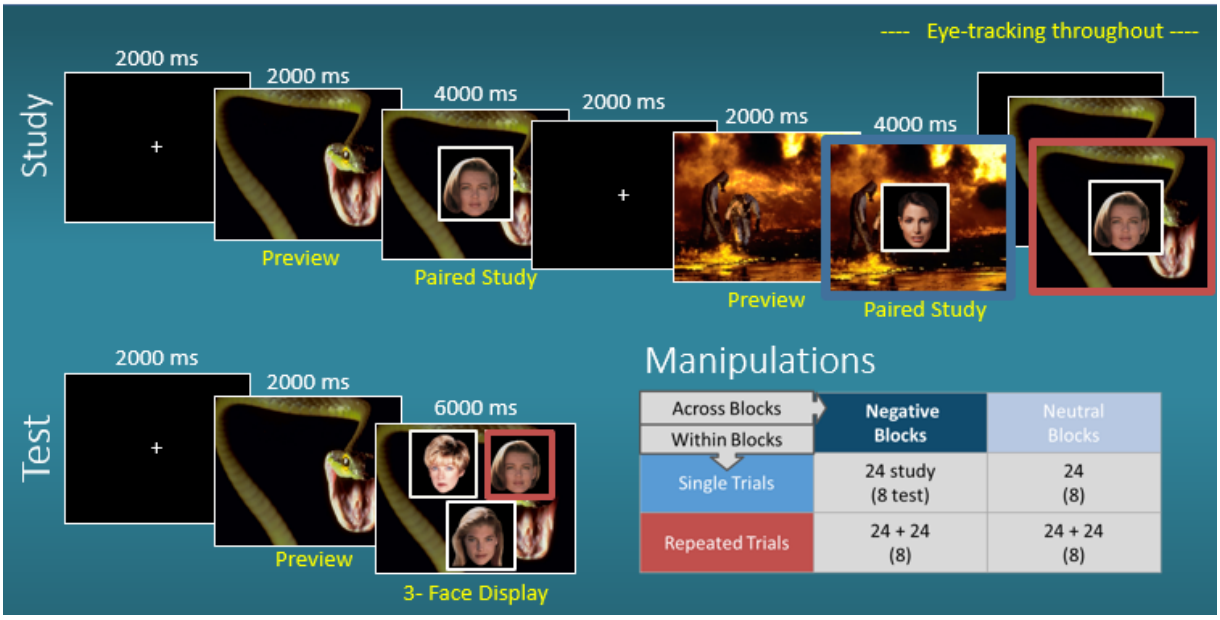


Figure 3.1: Schematic of the experimental design, timings, and conditions.

faces and scenes were randomized such that faces were paired with different scenes across the 4 versions. Second, block order was randomized so that in 2 versions the experiment started with a neutral block, in the 2 other versions the experiment started with a negative block. Lastly, within each version, the location of the target face (one that was studied the scene from the probed study trial) appeared equally likely (33% of trials) in all 3 face locations across all 4 conditions.

Eye Movement Analyses

Eye movement data was collected throughout the experiment and was analyzed separately within 4 experimentally meaningful periods—study time scene preview ("study preview"), study time face-scene paired viewing ("study paired viewing"), test time scene preview ("test preview"), and test time presentation of 3 faces on cued scene during recognition test ("test display"). Furthermore, study time eye movements were analyzed with respect to later recognition accuracy, in order to identify eye movements related to successful relational memory retrieval ("subsequent memory"). Of note, study time eye movement results for the repeated condition, unless otherwise specified, included only the *second* exposure of a particular face-scene display. The first exposure of a trial in the Repeated condition appeared no different to participants than a trial in the Single condition and therefore were not expected to contribute meaningful information to the examination of repetitions effects.

For each of the experimental time periods mentioned above, the following 4 types of summary measures were calculated from the eye movement data.

Viewing to the whole display. In number of transitions, summed across the entire viewing period across the whole screen area. This measure summarized how much participants

moved their eyes between the face(s) and scene during study and test, and was an index of active sampling of the display.

Viewing to a specific face within a display. Several measures were included in this category. First was a measure of viewing time to an element of a display as a proportion of total viewing to all elements presented ("proportion viewing time"). During study paired viewing, this was viewing to the face stimuli as a proportion of viewing time to the face and the scene. During the test display, this was viewing to a selected face, whether correctly (to the target face) or incorrectly chosen (to a familiar lure), as a proportion of viewing to all 3 faces. Different theoretical reasons motivated the calculation of this measure for the study versus test periods. At study, this measure represented the distribution of viewing between the face and scene at memory encoding. If emotion influences attention allocation during perception and memory encoding, we hypothesized that there would be less viewing to the study face compared to the scene for negative compared to neutral trials, potentially leading to differences in subsequent performance on recognition memory. At test, the proportion viewing to the target face provided an additional index to the amount of viewing a target face received across the whole trial.

Additionally, we also examined the number of fixations to the study face as a proportion of the total number of fixations made to the study display, and, at test, the proportion of fixations to the selected face, in relational to total fixations to all 3 test faces. The number of fixations directed to a stimulus is an additional measure of sampling to the stimulus. It has also been demonstrated to index the amount of detail contained within a memory representation for a sampled element (Riggs et al., 2010).

Proportion viewing that unfolds over time (time course). The measure was calculated as viewing to a test display face as a proportion of viewing to all 3 test faces, in increments of 500 ms time bins with respect to the onset of the test trial. This measure sought to replicate a relational memory eye movement effect well-established by previous studies (Hannula et al., 2007; Hannula & Ranganath, 2009). As an expression of relational memory retrieval, disproportionate amount of the total face viewing time (above chance level, or 33%) should be directed at the target face which completes the study time face-scene relational pair, during the initial time bins of the test trial.

Response–locked time course. This measure consisted of the same analysis as the proportion viewing time course with the exception that the viewing data was shifted to align by response time. Again, established by previous research (Hannula et al., 2007), disproportionate viewing to the correct test face should onset prior to the behavior response. By examining this measure, any differences in the retrieval speed for relational memory involving negative versus neutral information, independent of overall differences in response times, may be revealed.

To ensure eye movement data were from trials where participants had valid viewing of the display, all analyzed trial had to receive reviewing at least 33% of total period time. The minimum duration allowed for valid fixations was 83 ms.

Results

Behavior Performance

Repeated measures ANOVA was conducted on recognition accuracy with factors of Repetition (Single vs. Repeated) and Emotion (negative vs. neutral). Analysis revealed a main effect of Repetition, $F(1, 20) = 74.85$, $p < .001$. Participants were significantly more accurate at choosing the face that reinstated the study time face-scene relational pairing when the stimuli were seen twice during the study phase, compared to trials seen only once (Single $M = 59.5\%$, $SE = 2.7\%$; Repeated $M = 77.3\%$, $SE = 3.2\%$). No significant main effect of Emotion or interaction between Repetition and Emotion were identified (all F's < 1.09, all p's > .312). Therefore, negative emotion did not impair nor enhance participants' ability to remember relational information, nor did the effects of negative emotion change depending on the number of study opportunities (Table 3.1**)**.

Analysis of the response time (RT) data revealed a more nuanced pattern. There were significant main effects of Repetition and Emotion but no interaction, for RTs on Correct trials. Participants were significantly faster at the successful retrieval of Repeated trials compared to Single trials, $F(1, 20) = 30.23$, $p < .001$, (Single $M = 2685$ ms, $SE = 111$ms; Repeated $M = 2256$ ms, $SE = 96$ ms). Successful retrieval of negative trials was slower than neutral trials, $F(1, 20) = 9.227$, $p < .001$; negative $M = 2571$ ms, $SE = 112$ ms; neutral $M = 2370$ms, $SE = 91$ms). Importantly, no significant RT differences were observed for Incorrect trials for either main effects of Repetition or Emotion (all F's < 2.91, all p's > .11). Thus, RT main effects observed in the correct memory trials were due to memory-related processes rather than processing speed differences in the presence Repeated or Emotional stimuli.

			Response Time (ms)	
Repetition	**Emotion**	**Accuracy**	**Correct Trials**	**Incorrect Trials**
Single	**Negative**	0.58 (.03)	2801 (140)	2933(129)
	Neutral	0.61(.04)	2568 (104)	2941(151)
Repeated	**Negative**	0.76 (.04)	2341(105)	3161(167)
	Neutral	0.79 (.03)	2171(101)	3026(167)

Table 3.1: Accuracy and response times by Repetition and Emotion conditions (mean and standard error).

Median-split by valence ratings. Given that a main effect of negative emotion was identified in RT but not accuracy, this raised the possibility the effect of negative emotion on accuracy may be more subtle and required a more nuanced characterization of the data. Furthermore, as mentioned in methods, the full set of negative stimuli selected for this experiment consisted of a wider range of arousal values than would be used in most studies, and therefore may vary more greatly in their valence ratings than was ideal. To this end, we hoped to obtained a more nuanced analysis by performed a median-split of the experimental trials, selecting for the lower 50% of negative trials (M = 2.09, SD = .39) and the lower 50% of neutral trials by valence rating (M = 5.67, SD = .32) before subjecting the memory performance of the resulting subset of trials to a repeated measures ANOVA with Emotion and Repetition as factors.

Despite this more nuanced approach, the pattern of results for memory accuracy remained the same. A main effect of Repetition was found, F (1, 20) = 21.56, $p < .001$, with Repeated trials having significantly higher accuracy (M = 0.77, SE = .029) compared to Single trials (M = 0.63, SE = .034). No significant main effect of Emotion or interaction between Emotion and Repetition was identified (all F's < 1.67, all p's > .21).

Eye Movement Results

Results below, were investigated in the manner that best addresses our experimental questions, rather than examined in the experiment's chronological order. To this end, we first examined data from the retrieval phase, during presentation of the three-face alternative choice test display. We determined whether the current experiment replicated relational eye movement effects from previous studies, as well as explored effects of Repetition and Emotion on retrieval time eye movements. Once we established retrieval time effects, we investigated viewing behavior from other viewing periods that may contributed to the retrieval time result – namely, viewing behavior from test scene preview, study scene preview, and study paired viewing periods.

Test phase: time course analysis and relational memory effects.

Time course of preferential viewing to target face. First we examined the time course of viewing to ascertain whether the relational memory eye movement effect, namely, significant preferential viewing (greater than expect by chance, at 33%) to target face compared to that for incorrectly chosen lure faces, was replicated in the present study. Successful replication of this relational memory eye movement effect was found (Figure 3.2). Paired t-tests (Bonferroni corrected $\alpha = .008$) were conducted within 300 0ms of the display onset, an analysis window informed by previous literature (Hannula, Ryan, Tranel, & Cohen, 2007; Hannula & Ranganath, 2009), to identify time bins where viewing to correctly chosen target faces exceeded that of incorrectly endorsed familiar lure faces. Results showed that differences in preferential viewing between these two face types emerged at 500 -1000 ms after the onset of the 3 faces, $t\ (20) = 4.14$, $p < .001$, and there was a marginally significant difference that persisted for 1500 ms into the display presentation, $t\ (20) = 2.61$, $p = .0085$. Thus, the current study successfully replicated

the preferential viewing which indexes relational memory through eye movements. The timeframe of the current result was also comparable with the previous literature, which reported relational memory eye movement effects as early as 500 -1000 ms after display onset (Hannula et al., 2007).

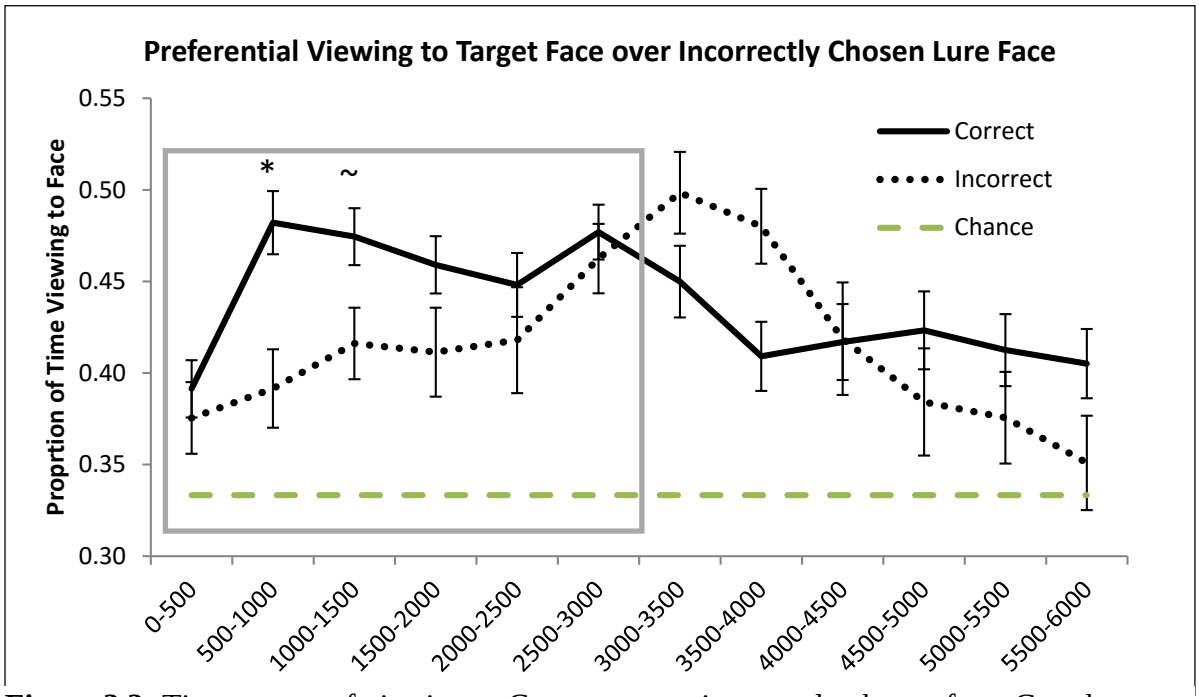


Figure 3.2: Time course of viewing to Correct versus incorrectly chosen face. Gray box indicates time periods tested by paired *t* tests (* denotes significance. ~ denotes marginal significance).

Repetition and emotion effects on time course of preferential viewing. After confirming the current study replicated the canonical relational memory eye movement effect, we investigated whether the time course of viewing to the target face was affected by Repetition and Emotion. A repeated measures ANOVA with factors of time bins (6 time bins of 500 ms durations), Repetition (Repeated or Single), and Emotion (negative or neutral) was conducted. The omnibus ANOVA revealed a significant main effect of time bins, F (5, 100) = 3.803, p =.003, which was qualified by an interaction between Repetition and time bins, F (5, 100) =

5.478, $p < .001$. Bonferroni corrected pairwise comparisons (corrected $\alpha = .008$) were then conducted to identify which time bins differed within Repetition. As shown in Figure 3.3, significantly greater preferential viewing to Repeated trials over Single trials occurred within 1500-2000ms of trial onset, t (20) = -3.051, $p = .006$, and marginally significant indications were found that showed this relationships was reversed later, between 2000 to 2500ms after stimulus onset t (20) = 2.384, $p = .027$.

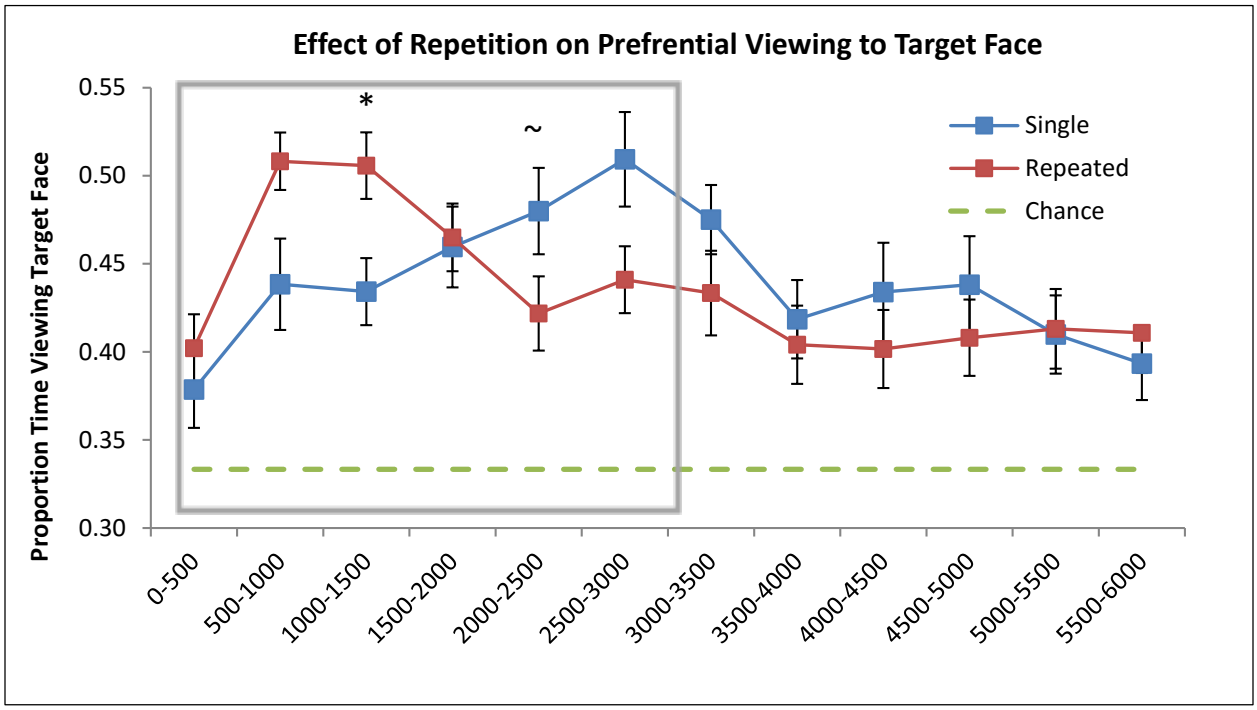


Figure 3.3: Viewing to correctly selected target face by Repetition condition. Gray box indicates time period tested by paired t-tests (* denotes significance. ~ denotes marginal significance).

Response-locked time course. To determine if the above-identified time course differences indexed variations in the speed of retrieval of the relational presentations, we examined eye movements to target faces aligned to the onset of the response for each trial (Figure 3.4**)**. A repeated measures ANOVA with factors of response-locked time bins (10 bins of 500 ms durations covering 2500 ms before and after response), Repetition, and Emotion was conducted. Greenhouse-Geisser corrected *p* values are reported below for sphericity violations in the time course data. This analysis yielded a significant main effect of time bins, F (3.87, 77.38) = 60.18, $p < .001$. This main effect was qualified by an interaction between Repetition and time bins, F (5.44, 108.84) = 3.94, $p = .002$. Bonferroni Corrected Pairwise comparisons (corrected $\alpha = .005$) revealed that the interaction arose from a marginally significant drop in disproportionate viewing to target faces for the Repeated trials, 500 ms after the peak of viewing to target faces, t (20) = -2.978, $p = .007$. There was higher viewing to Repeated trials at 2000-2500ms after response t (20) = 3.33, $p = .003$.

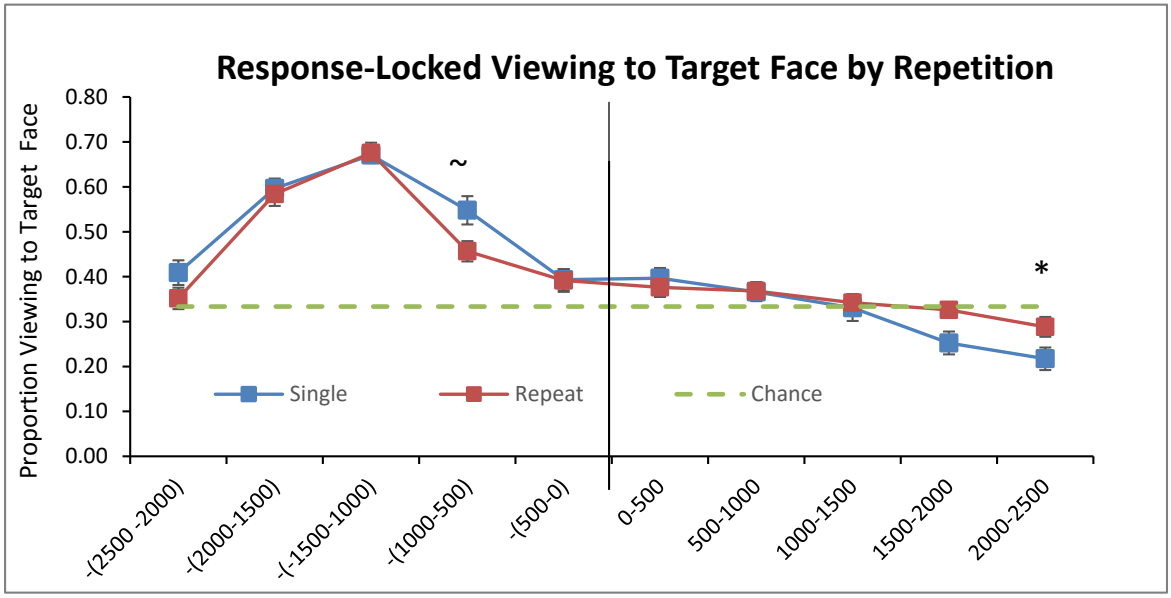


Figure 3.4: Response locked time course viewing to Correct face by Repetition condition. Vertical line indicates onset of response (* denotes significance. ~ denotes marginal significance).

Test phase: three-face display summary viewing effects.

Test trial viewing to target face. Summarizing viewing behavior aggregated across the entire duration of the test trial, we examined participants' average viewing to the correctly selected target face, as a proportion of viewing to all three faces presented. Results from a repeated measures ANOVA with factors of Repetition and Emotion showed identical patterns for the proportion viewing time and proportion of fixations measures. There were main effects of Repetition for both measures. Participants viewed the target face of Repeated trials more than that of Single trials, F (1, 20) = 36.13, $p < .001$ (Single M = 51.8%, SE = 1%; Repeated M = 57.3%, SE = 1%). Participants also had greater proportions of fixations on the target face for Repeated trials than Single trials, F (1, 20) = 25.80, $p < .001$ (Single M = 49%, SE =1%; Repeated M = 53.5%, SE = 1%). There was no main effect of Emotion or interaction between Repetition and Emotion for these measures (all F's < 1.45, all p's > .241).

Test trial viewing to entire test display. Summarizing the number of transitions made to the whole test display for the entire duration of presentation, main effects of Repetition and Emotion were revealed and no interaction. More transitions were made during recognition of Single trials than of Repeated trials, F (1, 20) = 46.63, $p < .001$; Single M = 4.22, SE =.27; Repeat M =3.36, SE = .24), as well as more transitions made to negative trials than neutral trials, F (1, 20) = 5.497, p = .029 (Negative M = 3.96, SE = .27; Neutral M = 3.61, SE = .25).

Test scene preview: display summary viewing effects. The presence of a scene preview is functionally relevant to the relational memory retrieval process; in the absence of a scene preview, expression of disproportionate viewing to the target face has been found to be delayed (Hannula et al., 2007). Thus, we reasoned that effects of Repetition and Emotion on relational memory may also be manifested in the eye movements during this period.

Eye movements to the scene preview revealed significant differences in the number of fixations to the preview scene, but not in participants' viewing duration of the displays (all *F*'s < 1.44, all *p*'s > 0.25). These results together indicate that participants did not avoid viewing the negative scenes but there were differences in how information was sampled from scenes of different repetition or emotional status. Specifically, for the number of fixations measure, a repeated ANOVA with the factors of Accuracy (Correct, Incorrect), Repetition (Single, Repeated), and Emotion (Negative, Neutral) was conducted. Three participants did not have Incorrect trial performances for Repeated conditions therefore this analysis was conducted on 18 participants with all behavioral trial types. The analysis revealed a marginally significant main effect of Repetition, F (1, 17) = 3.88, p = .065, in the direction of reduced number of fixations for Repeated trials (Single M = 5.41, SE = 0.17; Repeated M = 5.23, SE = 0.12), as well as a marginal interaction between Repetition and Emotion, F (1, 17) = 4.15, p = .058). Follow-up analyses revealed that the marginal interaction arose out of difference in fixations to Negative trials between Single and Repeated conditions, t (17) = 3.067, p = .007 (Negative Single M = 5.42, SE = 0.16; Negative Repeated M = 5.23, SE = 0.15), while no statistically significant difference existed in fixations to Neutral scene between Single and Repeated presentations t (17) = 1.537, p =.143 (Neutral Single M = 5.23, SE = 0.13; Neutral Repeated M = 5.36, SE = 0.18). As only one stimulus was presented during this period, proportion viewing measures were not applicable here for reporting.

Study phase: display summary viewing effects related to later memory accuracy. To inform the differences observed for test time behavior and eye movements, we examined study time viewing. The goal was to investigate whether sampling of the study display differed for Repeated versus Single trials, and Negative versus Neutral trials, in ways that related to later

memory. Thus, study trials were analyzed based on accuracy of test time recognition accuracy to identify subsequent memory effects. Consequent, subsequent memory effects were detected whenever a main effect of Accuracy was revealed to be significant in the study time analyses. As three participants did not have Incorrect responses in the Repeated condition, below analyses are based on the remainder 18 participants with response in all trial types.

Study Scene Preview: summary viewing analyses. Categorizing trials by subsequent behavioral performance, an omnibus repeated measures ANOVA with factors of Accuracy (Correct, Incorrect), Repetition (Single, Repeated), and Emotion (Negative, Neutral) was conducted for various eye movement measure derived from the study scene preview.

First, we examined the proportion of total time participants viewed the presented scene. This analysis was conducted to ascertain whether participants showed any avoidance in viewing of the negative scenes, such as by blinking or looking away from the screen. The omnibus ANOVA identified a significant main effect of Repetition, F (1, 17) = 6.71, p = .019, such that Repeated study scene preview received less viewing than preview for Single trials (Repeated M = 67.1%, SE = 1.4%; Single M =65.1%. SE = 2.0%). Critically, there was no evidence of avoidance of the negative scenes, as duration of viewing to Negative and Neutral conditions did not differ, F (1, 17) = 0.883, p = .36; Negative M = 66.8%, SE = 1.4%, Neutral M = 65.4%, SE = 2.2%). There were also no other significant main effects or interactions (all F's < 1.15, all p's > 0.153).

The number of fixations made to the preview scene differed significantly for the main effects of Accuracy, F (1, 17) = 8.57, p = .009, Repetition, F (1, 17) = 56.76, p < .001, and Emotion, F (1, 17) = 7.02, p = .017. More total fixations were made to subsequently Correct

trials than Incorrect trials (Correct M = 5.43, SE = 0.16; Incorrect M = 5.27, SE = 0.19); more fixations were made to Single trials than Repeated trials (Single M = 5.64, SE = 0.18; Repeated M = 5.06, SE = 0.18); more fixations were made to Negative trials than Neutral trials (Negative M = 5.50, SE = 0.17; Neutral M = 5.20, SE = 0.20).

Study phase: face-scene paired summary viewing analyses. The same omnibus repeated measures ANOVA with the factors of Accuracy (Correct, Incorrect), Repetition (Single, Repeated), and Emotion (Negative, Neutral) was conducted on study time face-scene pair viewing behavior.

First, on viewing to the study face, the proportion viewing duration to the study face revealed a subsequent memory effect (see Figure 3.5). Specifically, proportion viewing duration to the study face differed significantly for the main effects of Accuracy, F (1, 17) = 21.65, p < .001), Repetition, F (1, 17) = 5.32, p = .034, Emotion, F (1, 17) = 19.16, p < .001, and this was qualified by a significant 3-way interaction between Accuracy, Repetition, and Emotion, F (1, 17) = 6.21, p = .023. Follow-up analyses showed an interaction between Repetition and Emotion unique to subsequent Correct trials, F (1, 17) = 5.42, p <.033. For subsequent Correct trials, study time viewing to faces in Neutral trials remained the same across Single versus Repeated trials. However, viewing duration to study face was shorter for Negative Single trials than for Negative Repeated trials, t (17) = -3.29, p = .004 (Negative Single M = 7.16, SE = 0.02; Negative Repeated M = 0.76, SE = 0.02).

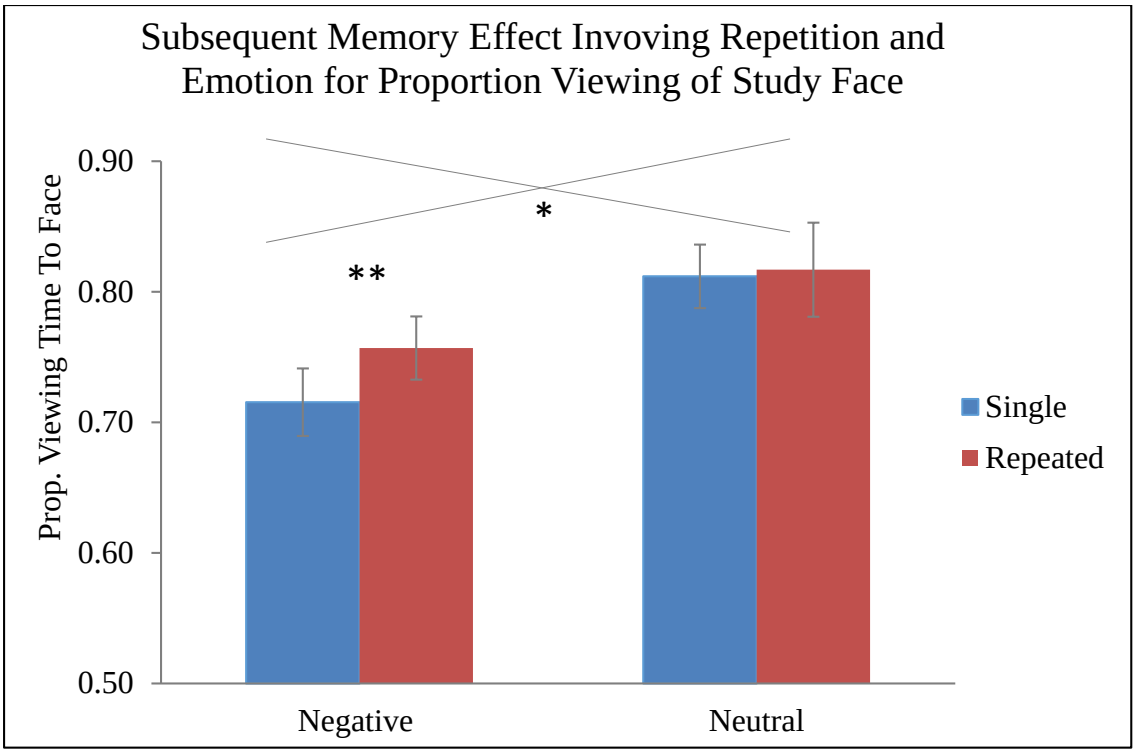


Figure 3.5: Viewing of study face as a proportion of study trial viewing. A subsequent memory effect was revealed, such that Correct trials (graphed above) received more study face viewing than Incorrect trial (not graphed). Furthermore, a significant interaction between Accuracy, Repetition, and Emotion showed significantly reduced viewing of the face at study for subsequently Correct Negative Single trials as compared to Negative Repeated trials (* denotes significance at $p < 0.05$, ** *at* $p < .01$).

Second, the measure of proportion of fixations to the study face revealed patterns that parallel the proportion viewing time findings. Namely, there was a main effect of Accuracy, $F(1, 17) = 28.53$, $p < .001$), Repetition, $F(1, 17) = 6.10$, $p = .025$), and Emotion, $F(1, 17) = 18.85$, $p < .001$), and this was qualified by a significant 3-way interaction between Accuracy, Repetition, and Emotion, $F(2, 17) = 5.06$, $p = .038$. Follow-up analyses showed interaction effects organized by Emotion. Neutral trials showed differences in the proportion of fixations to the study face depending on Repetition, $F(1, 17) = 6.42$, $p = .021$, such that faces in Neutral Repeated trials received greater proportion of fixations (Neutral Single $M = 79.7\%$, $SE = 2.5\%$; Neutral

Repeated *M* = 82.3%, *SE* = 3.0%). There were no proportion of fixations differences for Neutral trials depending on Accuracy, nor an interaction between Repetition and Accuracy (all *F*'s < 2.31, all *p*'s > .15). In contrast, Negative trials showed significant differences in the distribution of fixations between study face and scene depending on Accuracy, F (1, 17) = 10.13, *p* =.005. This was qualified by a near-significant interaction between Accuracy and Repetition, F (1, 17) = 4.29, *p* =.054. Simple main effects analysis within Negative trials revealed an effect of Repetition for subsequently Correct Negative trials, *t* (17) = -2.85, *p* =.011. The proportion of fixations to the study face was smaller for subsequently Correct Negative Single trials than for Correct Negative Repeated trial (subsequent Correct Negative Single *M* = 71.5%, *SE* = 2.6%; subsequent Correct Negative Repeated *M* = 7.7%. *SE* = 2.4%). There were no differences in proportion fixations to the study face for Incorrect trials regardless of Repetition, *t* (17) = -0.106, *p* = .917 (subsequent Incorrect Negative Single *M* = 69.6%, *SE* = 3.0%; subsequent Incorrect Negative Repeated *M* = 69.8%, *SE* = 3%).

Lastly, we examined the number of transitions between the face and scene ROIs. The omnibus ANOVA identified significant main effects of Repetition, F (2, 17) = 44.90, *p* <.001, and Emotion, F (2, 17) = 41.19, *p* <.001, but not of Accuracy nor interactions between the factors (all *F*'s < 2.99, all *p*'s > .102). Single trials had more transitions than Repeated trials (Single *M* = 2.02, *SE* = 0.12; Repeated *M* = 1.58, *SE* = 0.12). Negative trials more transitions than neutral trials (Negative *M* = 2.10, *SE* = 0.12; Neutral *M* = 1.50, *SE* = 0.12).

Median-split of trials by stimuli valence ratings and eye movement analyses. Akin to our rationale for employing this analysis on behavioral accuracy, we also conducted a median-

split of trials by valence an applied this to the various analyses for eye movement data, as a more nuanced and statistically sensitive approach to examine test and study phase eye movements.

For the majority of measures, the median-split selection yielded the same patterns results pertaining to Emotion and its interaction with Repetition. Below, we report instances where the median-split selection revealed *additional* significant results involving the Emotion manipulation that were not identified in the analyses involving the whole dataset, in order to highlight the subtler effects only detected via this analysis method.

Study scene preview: after median-split selection. Conducting the omnibus repeated measures ANOVA with factors of Accuracy (Correct, Incorrect), Repetition (Single, Repeated), and Emotion (Negative, Neutral) on eye movements to the scene during study preview yielded a significant interaction, which was not detected in the equivalent analysis for the whole experiment, between Repetition and Emotion for the number of fixations measure, F (1, 17) = 5.13, p = .037 (see Figure 3.6). Follow-up analyses revealed that the interaction arose out of a greater reduction in fixations to the Negative scene preview between the Single and Repeated conditions, t (20) = 4.96, $p < .001$ (Negative Single M = 5.89, SE = 0.19; Negative Repeated M = 5.39, SE = 0.20), than a similar reduction in fixations to the preview Neutral scene between Single and Repeated conditions, t (20) = 4.05, p = .01 (Neutral Single M = 5.59, SE = 0.23; Neutral Repeated M = 5.26, SE = 0.22). On the other hand, the number of fixations did not differ between Negative and Neutral scene previews with each repetition level (all F's < 1.77, all p's > .093). This same analysis also yielded the same pattern of significant main effect of Repetition F (1, 17) = 36.56 $p < .001$ (Single M = 5.64, SE = 0.20; Repeated M = 5.15, SE = 0.21), and a marginally significant main effect of Accuracy (Correct M = 5.48, SE = 0.19; Incorrect M = 5.31, SE = 0.22) as reported before for analyses across all trials of the experiment.

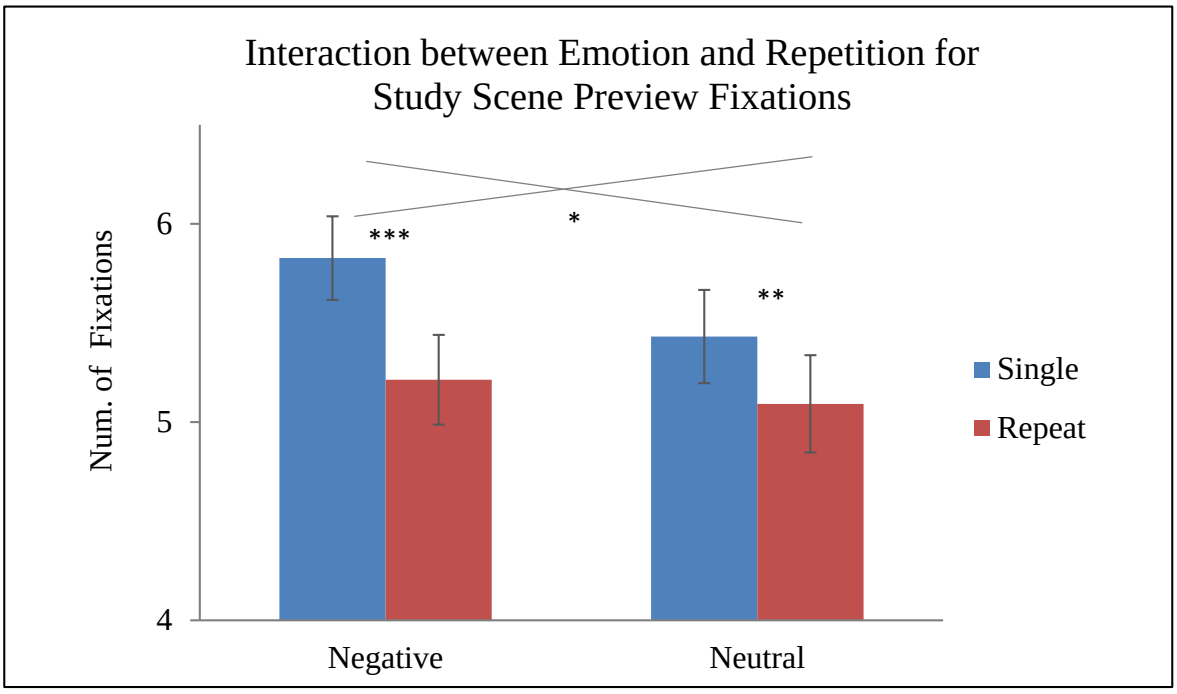


Figure 3.6: Number of fixations to study preview scene under median-split selection of trials. There was a significant interaction between Repetition and Emotion, among a significant main effect of Repetition. The reduction in number of fixations between Single and Repeated trials was greater in the Negative compared to the Neutral condition (* denotes significance at $p < .05$, ** at $p < .01$, *** at $p < .001$).

Discussion

The current study was devised to examine the effects of negative emotion on relational memory, as tested through recognition of studied face-scene pairs. Furthermore, a repetition manipulation was included as an opportunity to examine memory involving negative stimuli when the attentional influences of negative emotional stimuli may be minimized via repeated viewing. We discuss the findings on these issues below.

Negative emotion has subtle effects on relational memory

Behavioral results revealed robust effects of repetition both in response accuracy and response time while the effect of negative emotion was more subtle and was only present in RT analyses. The lack of negative emotion modulation of accuracy held true even when a more nuanced-analysis was adopted, by selecting for a subset of trials via median-split of the stimulus valence ratings.

The benefit of repetition on accuracy and response time suggests the formation of stronger, or more easily accessible, memory representations for information with multiple exposures. This is consistent with ample evidence on the effect of repetition during spaced study conditions (for review, see Smolen, Zhang, & Byrne, 2016). Additionally, repetition enhancing memory performance specific to relational information has been demonstrated in the form of better recognition of relational word pairs (Chua, Hannula, & Ranganath, 2012; Light et al., 2004).

The lack of accuracy differences by negative emotion observed in the current study does not equate to a lack of modulation of relational processing by negative emotion. Slower response times were observed for accurate relational memory involving negative stimuli. At the same time, no response time differences were observed between negative and neutral conditions given Incorrect response. Thus, the RT results suggest a change in the underlying relational representation by negative emotion.

Taken together, the accuracy and RT outcomes suggest that the effects of negative emotion within the current experimental design may be subtle and affect relational memory representation in ways that were not reflected in overt memory accuracy.

Relational memory eye movement effects track response time differences induced by repetition

A key strength of the current study design is its ability to afford a more sensitive probe of relational memory, in the form of eye movement derived measures, in addition to behavior accuracy. Previous studies employing this paradigm have firmly established an eye movement index of relational memory – the above-chance, preferential viewing to the target face which completes a learned face-scene pairing (Hannula & Ranganath, 2009; Hannula et al., 2007; Williams et al., 2010). Analysis of the time course of viewing to the 3 face test display in the current study replicated such an effect. Participants displayed greater preferential viewing to target faces that completed the studied face-scene relationship with the cued scene, than to incorrectly chosen lure faces.

Furthermore, novel to the current design, we could further query the effects of Repetition and Emotion on memory as observed through the expression of relational memory eye movement effects. Preferential viewing to target face emerged earlier for Repeated trials than for Single trials. This finding reinforces the observation from the response time analysis that Repeated trials were responded to faster.

To further elucidate and the relationship between this earlier onset of preferential viewing and the faster RT for Repeated trials, we conducted a response-locked analysis where viewing behavior was realigned to the onset of the reocognition rresponse. This analysis showed no differences in the timing of the peak of preferential viewing between Repeated and Single trials. In Repeated trials, however, preferential viewing decreased more quickly and sharply compared to the Single trials.

Taken together, the findings from both the stimulus-locked and response-locked analyses indicate that repetition lead to faster retrieval of relational memory representations and that preferential viewing time course was related with RT.

Whole trial viewing indices reveal modulation of emotion by repetition

Aggregating viewing behavior across the whole trial, several eye movement effects were identified to be modulated by negative emotion. We summarized data across 4 time points of the experiment – during 3-face relational recognition test, test scene preview, study preview, and study paired face-scene viewing. Main effects of negative emotion were identified from the recognition test phase given accurate relational recognition. That is, more transitions were made between the 3 possible response choices for the negative emotion condition to arrive at a correct response compared to Correct Neutral trials. There were also greater numbers of fixations devoted to test scene preview to negative scenes viewed only once, as compared to those in the repeated conditions that had an additional sampling at study time.

Since both of these test time results occurred under conditions of successful memory outcome for the Neutral and Negative conditions (i.e. given accurate relational recognition), they suggest modulation of relational representations by negative emotion at a more subtle level than overt behavioral accuracy. In this way, these test time eye movement findings corroborate with the pattern found in memory performance – that negative emotion manifests in the current study in more nuanced and fine-grained indices (such as RT) while no significant differences were detected in accuracy. This lack of overt memory modulation by negative emotion has been reported in studies probing source memory (Sharot & Yonelinas, 2008), or scene context

(Mather, Gorlick, & Nesmith, 2009). Findings from the current experiment therefore raises the interesting possibility that the lack of explicit accuracy effects in these studies may belie memory representation differences that can be detected using more sensitive methods.

Significantly, interactions between Repetition and Emotion were observed during the study phase. Per our predictions, if attention played a role in the current study performance, we would expect viewing to be different between Negative trials that have received one viewing versus those that have received a repetition. Indeed, we observed greater reduction in the number of fixations for Repeated conditions compared to the Single condition in the Negative trials, compared to the Neutral. During the face-scene study phase at study, there were less proportion viewing time and fewer fixations devoted to the study face for Negative Single trials compared the Repeated trials, while Neutral trials did not show significant differences in these indices. Furthermore, similar to the pattern now iterated from behavioral response and test time eye movements, these study time effects were observed for trials with correct memory. Hence, the change in viewing pattern in Negative trials across singular or repeated viewing is evidence that overt attention allocation changed during this task. However, the fact that these differences were observed for trials with successful relational memory performance, also suggests that attention allocation did not determine memory outcome; rather these results constitute further evidence for a modulating effect of negative emotion on the underlying memory representation.

Limitations and Future Directions

A limitation in the current study is the lack of normative eye movement measures for the IAPS emotional stimuli used. It is possible that negative and neutral stimuli also differ in how

information is distributed across a given image, and this may cloud some of the eye movement findings. For future iterations of the study, it would be clarifying to consider the visual complexity and distribution of visual information for negative and neutral trials, and to either account for, or equate them. In doing so, we may further dissociate the effects of attention allocation from our effect of interest – the modulation of relational memory representations by negative emotion.

CHAPTER 4: STABILITY OF RELATIONAL INFORMATION AS CONTEXT IN FACILITATING EPISODIC MEMORY

Abstract

Remembering daily events involves integrating items, locations, and the relationships between them. Some item-location relationships are stable across experiences (e.g. rooms in a building) while others are more frequently changing (e.g. people in buildings). We hypothesized that the presence of stable relationships could aid in the organization of memory, thereby improving memory performance. Participants studied pairs of object images in various positions on the screen. Some of the item-position relationships were constant (stable) across trials while other item-position relationships were trial-specific (non-stable). At test, participants reconstructed the study configurations by selecting individual items from an array and placing them in the appropriate positions, thus recreating studied pairings. Eye movement data were also collected to provide an additional measure of memory and to capture implicit organization in the reconstruction. Results showed a dissociation between item and relational memory performance. Stability did not affect item memory performance, however, relational reconstruction accuracy was enhanced by stability. Furthermore, eye movements between stable and control conditions differed in conditions of equated memory accuracy. This experiment provides evidence that stable information enhances memory, specifically for relations, and may impart a context-like influence on memory organization as revealed through eye movements.

Introduction

Context as Part of Episodic Memory Representation

Episodic memory is characterized by memory for specific instances of events. This involves remembering not only the intentionally encoded event-specific information but also the setting, or *context,* in which an event took place (for reviews, see Diana, Yonelinas, & Ranganath, 2007; Eichenbaum, Yonelinas, & Ranganath, 2007). For example, if a task required the recall of "the most recent purchase of a greeting card", the greeting card being the goal of the action, would be the event-specific information. Remembering "where" the card was purchased and for "what" occasion would constitute context information that occurred with the event information. The importance of such context information is its role in specifying an instance of card-buying as distinguished from all other instances.

The presence of event-specific and context components of episodic memory have been formalized in various ways in studies of episodic memory. For example, using participants' subjective assessments on the quality of memory, some experimenters distinguish between the feeling of "knowing" vs. "remembering" (Tulving, 1985). The former describes recalling event-specific information alone, while the latter describes recalling event information along with its concomitant context information. From the perspective of the underlying psychological processes, researchers map such remember vs. know assessments to the memory processes of "familiarity" vs. "recollection", respectively (for review, see Yonelinas, 2002). Further, neuropsychological studies motivate the idea that familiarity and recollection processing are associated with different mental representations. Recollection is postulated to rely on *relational* representation and operations that capture and make flexible use of interrelationships of the

elements within episodes (Cohen et al., 1997; Eichenbaum & Cohen, 2001). The binding of "where" and "what" information to event-specific information is an example of relational processing and representation. In contrast, familiarity memory signals are believed to arise from representation and processing of the event-specific or *item* information.

In sum, across all levels of analysis of episodic memory, whether at the level of the subjective assessments of "remember" versus" know", at the psychological processes level of "recollection" versus "familiarity", or taking into consideration the representational content of the memory to distinguish between "relational" versus "item" representations, all current discussions support a componential view – that there are event-specific items as well as context information that comprise of episodic memory.

Context Affects Memory

The presence of context in episodic memory is more than a mere consequence it being concomitant to the main event of interest. Context has been firmly established to affect memory. Preserved, or matching, context information between learning and retrieval confers memory benefits for event-specific information, this phenomenon is termed context-facilitation. Conversely, changing context information between encoding and retrieval has been demonstrated to impair memory performance, known as context shift detriment. Evidence of such context-dependent memory effects have been established via changing visual features of the to-be-remembered material, such as font and screen orientation (Graf & Ryan, 1990), screen location (Murnane et al., 1999), or the global environment between encoding and retrieval, such as underwater versus on land (Godden & Baddeley, 1975; for review, see Smith, 1994). Especially relevant to the present experiment is the demonstration of context-dependent effects

using visual image stimuli. Hayes, Nadel, and Ryan, (2007) presented images of objects superimposed on scenes during encoding. Recognition memory for the encoded objects were tested by presenting the studied objects with its context or alone a black background (constituted a context-shift between encoding and retrieval). Context shift significantly decreased recognition accuracy for the studied object compared to the context–intact condition, across a series of four experiments. Thus, this study provides evidence of context-dependent effects on memory elicited via image stimuli.

Context is Automatically Encoded

Even though the presence of context in any event is by virtue of its co-occurrence with the event-specific information and it is often not a part of intentional encoding, it impacts memory nonetheless. This leads to the question of how the phenomenon of context-dependent memory arises. One possibility is that context is encoded automatically. Indeed, evidence of automatic encoding of context has been demonstrated in fear conditioning studies in animals. In such paradigms, animals are exposed to an aversive stimulus (unconditioned stimulus, US) paired with the presentation of a neutral stimulus (conditioned stimulus, CS), with the goal of eliciting an aversive response to the presentation of the CS alone. During extinction, animals are repeatedly exposed to the CS without US. The goal of extinction is to render the initial conditioning response “extinct” and for the animal to not react to the CS with an aversive response. Interestingly, extinction training exhibited context-dependent effects. If extinction training is conducted in a different context from the original conditioning (such as a different chamber), the aversive response returns when animals are placed in the original conditioning context and presented with the CS. Thus, even though context information is not relevant to the

conditioning event itself, it is nevertheless encoded into memory, and further, has an effect on behavior response (for review, see Maren, Phan, & Liberzon, 2013; Rudy & O'Reilly, 1999). In humans, the before-reviewed studies on context-dependent effects on memory were carried out under circumstances where context encoding was not required by the task, and are also examples for incidental or obligatory encoding of context(Godden et al., 1975; Graf & Ryan, 1990; Hayes, Nadel, & Ryan, 2007; Murnane, Phelps, & Malmberg, 1999; Smith, 1994).

Context Organizes Episodic Memory

The observations that context is automatically encoded and consequently affects behavior hint at the importance of context in the organization of episodic memories. Indeed, investigations into this question have revealed that context may be fundamental to the organization of episodic memory. We review two sources of supporting evidence.

First, research have uncovered evidence that episodic memory representations may be hierarchically organized (Diana, Yonelinas, & Ranganath, 2007; Eichenbaum, Yonelinas, & Ranganath, 2007; Rondina, Curtiss, Meltzer, Barense, & Ryan, 2016; Shimamura, 2010), and context has been suggested to be an organizing principle within such a framework. For example, McKenzie et al. (2014) obtained simultaneous recordings from populations of neurons in the rat CA1, as the animals experienced several context-guided object association events. The animals were trained to distinguish between several event features –2 item pairs, 2 reward values (rewarded, not rewarded), 2 item positions in 2 testing chamber contexts. Similarity analysis of ensemble neural firing patterns revealed that event features experienced within the same context were more similarly represented, compared to the same category of features experienced across contexts. In other words, organization of neural representations of event features of the position,

valence, and item appear to be nested within each testing chamber context. This finding highlights the role of context as the organizing feature upon which other information are dependent.

Second, response order analyses in paradigms using free-recall test of memory reveal that items studied contiguously also tend to be recalled together (Howard & Kahana, 1999; Manning, Norman, & Kahana, 2013; Polyn & Kahana, 2008). These recall order phenomena have been formalized in the context maintenance and retrieval model (Polyn, Norman, & Kahana, 2009). It is proposed that there exist slowly evolving, internally maintained context representations that are associated with incoming event information to form episodic memories. The implication here is that context information at study organizes memory and we can observe the consequence of this in the order of recall. Relevant to the present design is the prediction that context information acts to organize retrieval of learned item information.

What Defines Context – Extant Evidence

Given that context is a defining component of episodic memory, that it impacts memory, and that it seems to be automatically encoded, there is great utility in understanding exactly what constitutes context information. Are there factors and stimulus characteristics that bias certain elements in an experience to be processed as "context"? Thus far, research has mostly examined the memory consequences and neural responses to context, while less effort has been dedicated to exploring the information characteristics of context representations.

In existing studies, context has been represented by a limited set of stimulus categories. First, context has been operationalized as spatially extended information. This constitutes the "where" information encountered in daily events. In animal research, the testing chamber is often

defined as context (see Rudy & O'Reilly, 1999). In human research, scene images are often used to constitute context in accompanying item stimuli used in tests of memory (Duarte et al., 2011; Hannula et al., 2007; Hayes et al., 2007).

Second, context information has been defined by the circumstances under which the task-relevant information was initially encountered, often referred to as "source" information. Stimulus features or cognitive tasks performed in relation to task-relevant items are common types of source information that serve as contexts that help distinguish between study items. Such source contexts can be considered to correspond to the "what" or "occasion" information in everyday episodic information. Examples of stimulus feature as source context include screen locations (Cansino, Maquet, Dolan, & Rugg, 2002; Yu et al., 2012) and colors (Staresina & Davachi, 2008; Tendolkar et al., 2008); examples of cognitive tasks as source contexts include judgments of animacy and commonness of the studied items (Kensinger & Schacter, 2006a; Ranganath et al., 2003) or gender and size (DuBrow & Davachi, 2013).

Hypothesis--Context as Relational Stability

An unexamined issue with the above definitions of context is that they do not provide insight into what information characteristics may bias elements in episodic memory to be processed and represented as context. Such knowledge is pivotal in advancing our understanding episodic memory representations for everyday events, as daily experiences do not tend to contain pre-defined delineations of scenes versus objects nor pre-specified task goals to be designated as context.

The current experiment tested a novel hypothesis that, in the absence of strong demands organize event information in certain ways (e.g. based on study instructions), *stability of*

information across repeated experiences is the critical characteristic that biases some elements within an event to be processed and represented as context in episodic memory. On the other hand, information that changes from encounter to encounter are biased to be encoded as event-specific or item information. For example, consider the aforementioned instance of an episodic memory on card-buying. Assuming the "where" context involved was a drugstore. There is a collection of event features that are likely to be constant, or "stable", across visits that constitutes "drugstore" information, such as the dimensions of the space, the location of the checkout counter in relation to the entrance, and the layout of the display aisles. On the other hand, a myriad of other information within the context of "drugstore" likely changes from visit to visit, such as the merchandise on offer and other customers who happen to be in the store. We hypothesize that such non-stable information is represented as event-specific information.

Additionally, we hypothesize that it is specifically the *stability of relational information across experiences,* as opposed to item information, that biases information to be processed and represented as context. Here, we define relational information as the interrelationship between discrete elements or features within an experience. Item information, on the other hand, is knowledge of the identities of individual elements and features in an experience, not considered in concert with other pieces of information.

Our working hypothesis is motivated by multiple lines of evidence, such as neuroimaging studies of context, analysis of scene contexts employed in experimental settings, and observations of situational contexts. We review the evidence and reasoning for each below.

Insights from neuroimaging evidence of context. Investigations into the neural correlates of context have identified multiple types of information that seem to correspond to

episodic context, as indexed by the parahippocampal cortex (PHC) neural activity. For example, studies first established the PHC is involved in the processing and representation of scenes encoded as source information for studied items (Gold et al., 2006; Staresina et al., 2011). The PHC has also been strongly implicated in the processing of visuospatial stimuli in studies without an explicit memory component, such as during perception or navigation (Epstein & Kanwisher, 1998; Epstein, 2008; Russell Epstein, Graham, & Downing, 2003; Goh et al., 2004). These lines of evidence led to the proposal that a domain-specific, scene-mediated representation underlies what is often evoked as "context" in episodic memory (Epstein & Ward, 2010). However, other studies have established PHC sensitivity to context information not involving scenes, such as to source information (Diana, 2016; Gottlieb, Wong, de Chastelaine, & Rugg, 2012) and to visually similar scenes with varying degrees of context associations (Bar, Aminoff, & Schacter, 2008). Taken together, these neuroimaging evidence suggested that context is likely *not* specific to the domain of scene information but can consist of a wide range of information types. The variety in information consisting context led us to explore the idea that there may exist a more fundamental information property that biases information to be processed as context. We arrived at the hypothesis that *relational stability* is such a property by considering its possible role in extant studies of using scenes and situational contexts.

Relational stability as scene context. Scene context often consists of location information or spatially extended stimuli in experimental settings. We argue that both of these instantiations of context can be viewed as comprising of a multitude of relational information that is stable across encounters. For example, an "office" scene is informed by the constant co-occurrence of many office furnishings (desks, chairs) arranged in an ordered manner with respect

to each other (desks positioned in front of chairs) and with respect to an indoor space. The first stable relationship mentioned above, of the co-occurrence of chairs with desks, is an example of stable item-item relation. The spatial arrangement of the furniture with respect to each other, and to the indoor space, constitutes examples of stable item-location relation.

The *relational* nature of the stable information is pivotal to our hypothesis because item information alone does not adequately specify a particular context. The same items can be present in many events and episodes; sometime they may be more context-like than other instances. For example, the presence of office furnishings, without specifying their relationship to each other or the relationship to a location, could signal anything from an office to a furniture warehouse to a junkyard. Therefore, only when the relational information between items is specified, and is stable or predictable across experiences are those items involved more likely to signal a specific instance of context information.

We believe this same logic of stable item-item and item-location relations as a signal of context generalizes to all scene stimuli. Therefore, in considering information properties that may impart "context" information in scenes, we find relational stability to be a common underlying property.

Relational Stability in Situational Contexts. In everyday situations, there are many instances of context that do not involve locations or scenes. Consider the context of a "birthday celebration". This context is not defined by a location or a particular visual scene. Rather, it is defined by the unchanging relationship between a particular date and a person, and between a particular date with celebratory items (such as presents and cards). Both these features are examples of stable item-temporal relationships that define context.

Source information is another example context that do not involve scenes but may be reinterpreted with the same framework of relational stability as context. Behavioral tasks or stimulus features used as source context consists of the stable relationship between the source task or feature, the studied stimuli, and the duration of the experiment. For example, it is highly likely that participants have made animacy or size judgments on objects outside of experimental settings. What makes these judgments contexts in any given experiment is that they were performed in relation to studied items (such as word lists, or object pictures) taking place within the experiment.

Experimental Design -- Testing Context as Relational Stability

To test the hypothesis that relational stability biases processing of those event features involved as context, we devised a study that contained stable relational features across multiple trials, as well as trial-specific information which changed from trial to trial. Based on our hypothesis, the stable relations should be context-like and impart influence on the trial-specific, item-like information. In the experiment, participants studied two object-object image pairs occupying two screen quadrants in each study trial. Each pair of object images consisted of a smaller image superimposed over the center of a larger object image. All trials across an experimental block were formulated by repeated sampling 2 images from a set of 4 large object images and 2 images from a set of 4 small object images, as well as sampling from 2 of 4 large screen quadrant locations, and 2 of 4 small screen locations, to house the selected object images.

Context-like, stable relational information was operationalized as consistent item to screen location mappings of subsets of the stimuli. Specifically, two object stimuli in each study trial always occupied the same screen locations in all trials where they we sampled to appear.

The remaining two object stimuli represented event-specific information and appeared in multiple screen locations across trials where they were sampled to appear. Importantly, since the same stimuli sets were used across all trials of a block, chance level performance was the same for each stimulus type (choosing 2 out of 4 possible alternatives). This was done to ensure no factors other than relational stability differed between the context-like features and trial-specific features, and that any memory differences observed would necessarily arise from the stability manipulation.

Interaction with Stimulus features. Of additional interest to the present study was the question of whether stimulus properties associated with stable information was important. Could the context-like, memory influences of relational stability interact with visual and temporal properties of the object images through which stability was conveyed?

To test for the interaction between stability and stimulus properties, the stable item-location mappings was implemented through either the bigger object or via the small central image. This information further interacted with the order of presentation, such that the object carrying the stable item-location mapping either appeared first or second in each screen quadrant.

We felt it important to investigate the interaction of stimulus size and presentation order in conjunction with the stability manipulation because these stimulus features are common to previously mentioned scene and source contexts. Specifically, the big object images in each quadrant pair may be akin to scene contexts because they were the backgrounds to the central images, which, in turn, may be more akin to “item” information. Appearing first, rather than second, in a quadrant mimics the property of situational contexts as they tend to be established before event-specific information is perceived and encoded in everyday life (for example, we

tend to know that we are going into the office before we perceive the particular events unfolding in the office on a given day).

Therefore, the stimulus properties of being "background" and perceived "first" are two heuristics that are present in many instances of context. It may be possible that relational stability would produce the most pronounced memory effects when presented in conjunction with both these stimulus characteristics. Alternatively, if relational stability is a strong deciding factor of context processing, and that "background" and "first" stimulus properties are merely coincidental properties of common examples of such stability, stability-dependent memory effects should be similar across all conditions, regardless of the stimulus property involved in conveying such stability.

Dependent measures. Given the automatic processing of context which results in the context dependency of memory, we took reconstruction accuracy of the studied events as an index of whether relational stability was utilized as context in our study. If stable item-location relationships were utilized as context, we would predict better memory for the event-specific information during reconstruction tests, conforming to a context-facilitation effect.

Furthermore, motivated by evidence that context organizes episodic memory representations and thus influences response order in free recall, we also collected data on the order in which participants reconstructed the studied events (Howard & Kahana, 1999; Manning et al., 2013; Polyn & Kahana, 2008). If stable relational information engenders context-like effects and influences memory organization, there may be systematic patterns in reconstruction order associated with conditions with relational stability.

In addition to explicit memory recall, we further collected eye-movement data during the experiment. Previous research have established eye movements to be implicit indices of memory, such that visual exploration patterns consistently differ between familiar and novel stimuli (Althoff et al., 1999; Althoff & Cohen, 1999) and that retrieval time eye movements distinguish between intact and non-intact relational memory (Hannula, Ryan, Tranel, & Cohen, 2007; Hannula, Tranel, & Cohen, 2006). The continuous nature of eye movement data also makes them powerful supplements to the overt, binary measure of behavioral accuracy in detecting memory differences. If the presence of relational stability affects memory organization, we would expect systematic visual sampling differences during retrieval for conditions with stability compared to those without.

Lastly, the reconstruction format of test period in the current experiment supported the examination of stability-dependent memory effects separately for items versus relational information. The ability to examine these two types of information separately is a novel contribution in the study of context-dependent memory effects, as the majority of published studies involve testing memory for item memory only. If context representations help the organization of episodic memory, we would expect better memory performance for both item and relational information. However, if context mainly serves to buffer memory for trial-specific information but not the entire memory episode, we would expect recall benefits to item information only, when relational stability was present.

Methods

Participants

Thirty-one people between the ages of 18 to 35 were recruited from the University of Illinois community and compensated for their participation in the experiment. Two participants failed to complete the experiment and were excluded. Data from 29 participants (6 males, age *M* =22.50, *SD* = 4.43) were included in subsequent analyses.

Stimuli

Experiment used 96 color photographs of common objects taken from Baym and Gonsalves (2010), supplemented with additional images from Internet searches (Google Image Search). Each photograph consisted of a single object centered on a white background. Images were randomly divided into 2 groups. One group formed the spatially extended “backgrounds” (B), the other group formed the central “insets” (I). Images within each group were further divided into 12 sets of 4 images. For each experimental block, 2 sets of 4 backgrounds and 2 sets of 4 inset images were used. For practice trials, 8 photographs of scenes and 8 text symbols (@#$%&=) on solid color squares were used.

Apparatus

Eye movements were recorded at a rate of 1000 Hz using an Eyelink 1000 eye-tracking system (SR Research, Ontario, Canada). A chin and forehead rest 60 cm from the screen was used to support participants head and to minimize movement during eye tracking. All stimuli

were presented on a 21” LCD color monitor with a 4:3 aspect ratio, using Presentation (Neurobehavioral Systems, http://nbs.neuro-bs.com) on a Windows-based computer.

Design

The experiment consisted of 6 blocks of trials, preceded by 6 practice trials. Experimental conditions were manipulated between blocks such that each block contained trials from one experimental condition only. Within each block, trials were presented as alternating 2 study -2 test trials, with a total of 36 study and 36 test trials per block, or equivalently, with 18 of the 2-2 study-test sets, per condition. The 2-2 study-test sets were constructed to increase task difficulty and to avoid at-ceiling memory performance, as had been determined by pilot versions of the experiment.

Study trials consisted of a black screen (1600 by 1200 pixels) implicitly partitioned into quadrants. In any given study trial, two pairs of object images appeared on the screen, occupying 2 out of the 4 quadrants. Each of the 2 image pairs consisted of a **background image (B)** measuring 500 by 500 pixels, with the central area measuring 200 by 200 pixels obscured by a black square. An **inset image (I)** measuring 200 by 200 pixels would occupy the central square, thus forming a **background-inset pair (B-I pair)** in a quadrant. The image stimuli appeared sequentially, with images occupying the same quadrant appearing consecutively. Depending on the experimental condition (see below), either the background or inset image was first presented in an occupied quadrant (see Figure 4.1).

Study trials in each block were constructed by repeated sampling of 2 items out of 4 options for each stimuli type and location. For example, each study trial consisted of 2 background images sampled from a set of 4 background images. Thus there were 6 possible

ways of selecting 2 background images to be presented in a given trial. Similarly, there were 6 possible ways of selecting 2 inset images and 6 possible combinations of 2 screen locations. Together, the background and inset images, and their respective locations, could make up a combination of 216 unique trials. From this pool of trials, the following criteria were then implemented to pseudorandomly select study trials for each block: 1) all possible combinations of choosing 2 out of 4 options for each stimuli type and for screen locations were displayed at least once; 2) each of the 6 possible combinations of stimuli or locations were shown roughly equal numbers of times; 3) no same 4 image stimuli (even if shown in different screen locations) were repeatedly. In other words, all study trials differed in terms of which 4 object images were presented on screen. Lastly, in order to differentiate the study trials in each 2-2 study-test set, two lots of 4 backgrounds and 4 insets images were used, one lot for each study trial in the 2-2 study-test set. In this way, each block utilized 8 background and 8 inset images in total (see also experimental conditions section).

Test trials required participants to recall and reconstruct, in any sequential order, the 2 B-I pairs and their quadrant locations as presented during study. The test screen was divided into 4 quadrants, identical in dimensions to the study configuration. Within each quadrant were gray boxes delineating locations that images could occupy. Specifically, a gray box measuring 500 by 500 pixels in each quadrant indicated where the background images could occupy (hereafter "**venues" (V)**). Within each venue, a box measuring 200 by 200 pixels indicated where the inset images could occupy (hereafter **"sockets" (S)**). Furthermore, flanking the left and right sides of the test quadrant display, respectively, was a columns of 4 background images (200 by 200 pixels in size) and a column of 4 inset images (200 by 200 pixels in size), containing the stimuli used in the associated study trial. In other words, within each 2-2 study-test set, the first test trials

contained the lot of 4 background and 4 inset images used in the first study trials; the second test trials contained the lot of images from the second study trials. Participants directed a mouse cursor on the screen to click and "pick up" images from the side columns, and to click and "drop off" the images to occupy the venues and sockets. The test setup was constrained so that only background images were candidates for the venue spaces, and only inset images were able to be dropped into the inset spaces. The background images expanded to fit the venue spaces (from 200 by 200 pixels to 500 by 500 pixels) once participants clicked to designate them to particular screen locations.

Stability Manipulation

The main goal of this study was to impart underlying structure to the study information and to observe changes in memory performance related to the presence of such underlying organization. We operationalized structure as *stable stimulus-location relationships* involving repetition of the same set of stimuli across multiple trials. In other words, a portion of the presented stimuli in each trial (e.g. backgrounds) was designated to occupy the same screen locations (venues) throughout study trials in a block. Should a particular stable stimulus appear in a given trial, it occupied the same location as in all other study trials where it was present. Furthermore, we examined whether stimulus properties –such as the spatial extent of the stable stimuli (backgrounds vs. insets) and their temporal order (first vs. second, in a pair)—interacted with the stability manipulation and affected the degree of changes in memory performance. As such, the present experiment systematically varied the spatial extent and the temporal order of the stable relations, to examine whether these properties are critical for, or facilitate, the effects

of stability structure on memory performance. In total, four experimental conditions and two control conditions were constructed, as explained below (also see Figure 4.1).

	Stability/Experimental Conditions		Control Conditions
Stable Stimulus Presentation Properties	**Background**	**Inset**	**(No Stable Bindings)**
First	Background-Location Inset-Location	Inset-Location Background-Location	Background-Location Inset-Location
Second	Inset-Location Background-Location	Background-Location Inset-Location	Inset-Location Background-Location

Figure 4.1: Figure detailing the structure of the conditions in the study. The 4 cells on the left in blue indicate the 4 experimental conditions with a stable item-location manipulation. Orange texts indicate the class of stimuli that had stable, or consistent screen locations within a block. Gray texts indicate the relational information that was trial-specific. The gray column on the right indicates 2 control conditions where there were not stability and all information was unstable or trial-specific.

First, all conditions (both experimental and control) varied in terms of the *temporal order* of the stimuli presentation–either background items appeared first or inset items appeared first in each quadrant. Second, the experimental conditions varied by *spatial extent* of the stable information—the stable stimulus-location relationships either involved spatially extended backgrounds in venues (B-V) or the spatially centralized insets in sockets (I-S). In this way, the four experimental conditions that varied in terms of the temporal order and spatial extent of the stable stimulus-location relationships were as follows: (1) relational stability was conveyed via background images in venue locations, being the first image to appear in that quadrant (condition BVfirst**)**. In this condition, the background-venue mappings were stable. Whenever a background image appeared across the trials in a block, it occupied the same venue. Furthermore, the

background images were the first stimuli to appear in each quadrant, followed by inset images; (2) relational stability was conveyed via inset images in specific socket locations, appearing first in each quadrant (condition ISfirst), followed by background images. In this condition, the inset-socket mappings were constant. Whenever an inset image appeared across the trials in a block, it occupied the same socket location. Furthermore, the inset images were the first to appear in each quadrant, followed by background images; (3) relational stability was conveyed via background images in venues, appearing second in each quadrant (condition BVsecond); (4) relational stability was conveyed via inset images in sockets, appearing second in each quadrant (condition ISsecond).

The control conditions did not contain stable stimulus-location mappings. All items appeared in all quadrant locations across the trials of a block. The two control conditions differed in stimulus presentation order. In one condition, the background images appeared first in each quadrant, followed by inset items (condition BFirstControl). In the other control condition, the inset images appeared first within each quadrant, followed by background images (condition IfirstControl).

Lastly, it is worth emphasizing again, that across both stimuli dimensions, there were equally 4 pieces of information from which 2 were sampled per trial. This was done so there were equal amounts of information in both sized image domains. In this way, memory differences as a result of different stimulus properties of the stable information could not be attributable to varying amounts of information between differently size stimuli.

Procedure

Eye movements were collected throughout study and test trials. A 9-point eye-movement calibration was conducted at the beginning of each block. Before the start of the experiment, 6 practice trials were administered whereby experimenters explained the 2-2 study-test format of the trials in each block, and allowed the participants to become familiar with the drag-and-drop interface utilizing the computer mouse for the test trials. Participants were instructed to study the presented pairs and reconstruct them as best as they could at test. Importantly, participants were not informed of the existence of stable stimulus-location mappings. Participants completed 6 blocks in total, with each block corresponding to one experimental or control condition. Four versions of the experiment were generated whereby the order of the conditions across the 6 blocks were randomized.

Timing of each study trial consisted of presentation of a fixation cross in the center of a black screen for 1000 ms, followed the sequential appearance of 4 stimulus images in 1500 ms intervals, completing a pairing in one quadrant and then another pairing in a second quadrant. As mentioned in the design section above, four counterbalances of the experiment were constructed so that stimulus set to experimental condition assignments were randomized. The test trials were self-paced; participants had as much time as needed to reconstruct each trial and pressed a button to proceed when they were felt satisfied with their reconstruction (see Figure 4.2).

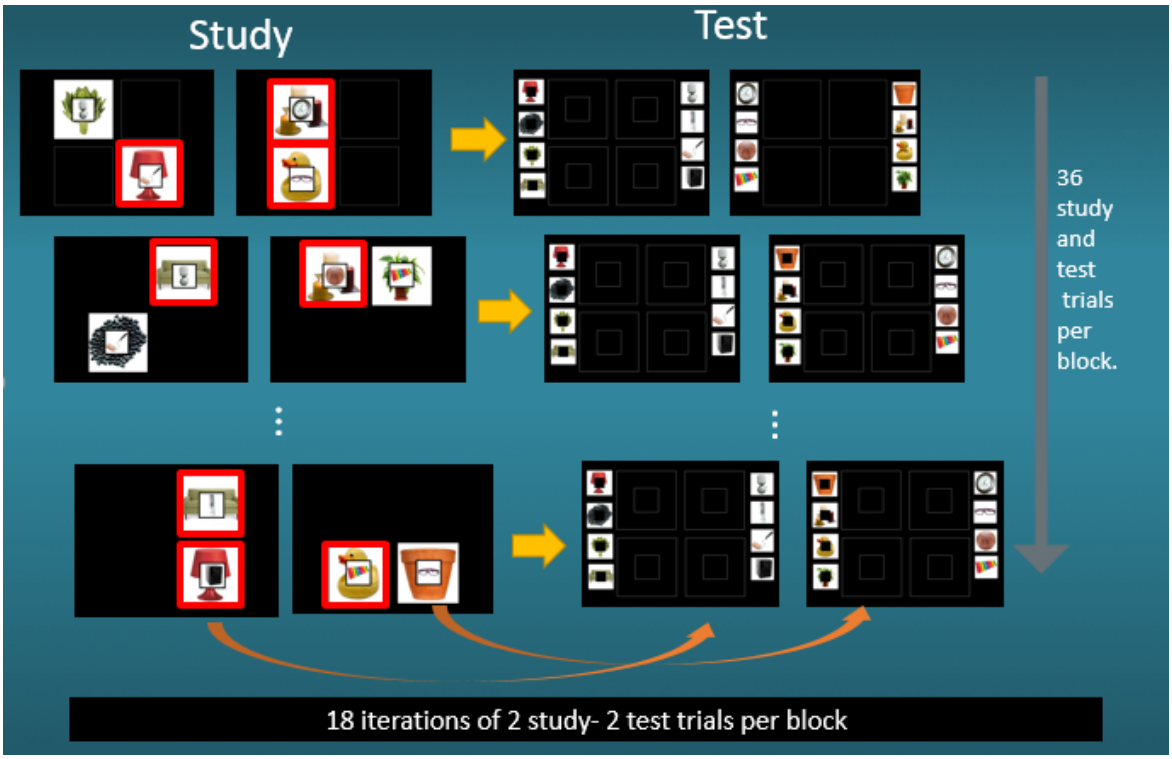


Figure 4.2: Schematic of the experimental design and procedure. Participants learned 2 study trials then immediately reconstructed 2 test trials. This was repeated 18 times in a block, making up 36 study and test trials in total, in a 2 study-2 test interleaved manner. Bottom arrows in the figure highlight the relationship between the study and test trials and that they contained distinct sets of stimuli. RED BOXES: highlighting the stable item-location elements that can be perceived from the examples trials shown.

Behavioral Analyses

The free-reconstruction format of the experiment, as well as a design involving the same number of units of information in multiple stimulus domains (2 backgrounds, 2 insets presented in 2 venues and 2 sockets), provided a rich configuration of behavioral responses. We characterized participants' memory performances in multiple ways.

Contrasting experimental versus control performance. Given the main objective of this study was to test the operationalization of context as stability of relational information in benefitting memory performance, the most immediately illuminating analysis was to contrast

memory performance between experimental conditions with relational stability and control conditions without any stability.

Differentiating between items and relations. Trial information was conceptualized as item versus relational information. This differentiation was motivated by previous research that suggests separable behavioral responses, cognitive processes, and neural substrates concerning item versus relational information (for review, see Diana, Yonelinas, & Ranganath, 2007). If, as previous evidence suggests, two separable processing streams contribute to the successful representation of episodic memory, relational stability may impact these aspects of memory differently, such that one may be impacted more than the. If this were the case, such memory differences would be detectable by the item and relations metrics conceptualized here. The next section details the determination of item versus relations information in the current experiment.

Items versus relations trial components. In terms of component parts of trial information, each test trial can be conceived as constituting of 4 pieces of non-relational information (hereafter **"items"**) that were the 4 image stimuli (2 smaller inset (I) images and 2 background images (B)). There were 2 **locations** that were the occupied screen quadrants (each containing 2 big venues (V) and 2 small sockets (S)). The *interrelationships* formed by the items (hereafter "**relations**") can be characterized as — 2 **item-item** relations (2 background-inset pairs (B-I)), 2 **location-location** relations (2 venue-socket pairs (V-S)), and 4 **item-location** relations (2 background-venue pairs (B-V), 2 inset-socket pairs (I-S)).

There exist additional ways to parcellate the rich set of trial information in this study that we have not adopted (such as considering within-modality relations such B-B, or I-I, and V-V

and S-S), however, listing all possible pairwise relationships would result in redundant information being captured by multiple measures. The above listed measures are also ones that we believe best answer our experimental question and make contact with existing literature. In sum, the measures of interest reported consist of -- 4 stimulus items (B, B, and I, I), 2 locations (screen quadrants), 4 item-location relations (2 B-V, 2 I-S), and 2 item-item relations (2 B-I).

Stable versus unstable trial components. Each of the various item or relational components detailed above were present in both experimental and control conditions. In the experimental conditions, a subset of the components conveyed the stable item-location manipulation, and we refer to these as the "**stable**" components. The other subset of trial components had locations that changed from trial-to-trial, and we refer to these as the "**unstable**" components. In the control conditions, since no relational stability was manipulated, all components are considered "unstable".

Furthermore, within any experimental condition, there were 2 stable item-location relations and 2 unstable item-location relations. Consequently, all item-item relations from experimental conditions consisted of an item from the stable category, and the other from the unstable category. For example, in the BVfirst condition, the stable relations were 2 B-V, the unstable relations were 2 I-S; the item-item relations (2 B-I), consisted of a stable item B paired with an unstable item I. In control conditions, item-item relationships were always formed from 2 unstable items.

By distinguishing between stable versus unstable items *within* experimental conditions, we could ask the critical question of whether the presence of stability benefited memory only for

the components involved, or whether having stability also boosted memory for the unstable components of the trial, and thus having context-like memory organizing and facilitating effects.

Eye Movement Analyses

Analyses of eye movements followed a similar structure to those outlined in the behavioral analysis section. Namely, the most illuminating comparisons were those between experimental and control conditions. What is unique to eye movements, is the way in which they can be summarized to reveal different facets of mental processing involved in a particular task performance. We detail these methods below.

Defining regions of interests (ROI). We defined a number of screen regions that corresponded to the display configurations on the screen. Viewing within each of the pre-defined areas, or regions of interest (ROI), indexed how much any given stimulus was sampled in each trial.

Concretely, for the study phase, we defined 8 ROIs, corresponding to 4 venues and 4 sockets where stimuli could appear. For the test phase, we defined 16 total ROIs, consisting of the same 8 ROIs as the study phase, where the object images could eventually be placed, and 8 ROIs corresponding to the side locations where 4 background items and 4 inset items resided at the onset of each test trial.

Eye movements that fell outside of these ROI's were recorded but excluded form subsequent analyses as they did not correspond to eye sampling of meaningful or interpretable information on screen relevant to the current study.

Entropy of transitions as an index of memory. There are many ways to summarize eye movements across ROIs, such as to descriptions of the amount of time, or the number of eye fixations devoted to each ROI (Hannula et al., 2010). However, while these measures provide good descriptive information on how displays are visually sampled, or how overt attention is distributed, they may prove to be less diagnostic of the underlying mental processes for the self-paced, reconstruction format used in the test phase of the current experiment.

To better address our objective of examining the effects of stability on memory, we sought to employ eye movement measures that are well-established indices of memory. To this end, we adopted an *entropy* calculation that has been repeatedly shown to index memory. In brief, eye movement entropy (hereafter, "entropy") was calculated by reducing trial fixations to ordered sequences of transitions between ROIs. Consecutive fixations within the same ROI without intervening fixations in other ROIs did not contribute towards the transition count. Additionally, trial fixations were considered valid if their duration exceeded a threshold of 83 ms (see Althoff et al., 1999, and Althoff & Cohen, 1999, for further details on entropy calculations).

The entropy measure, bounded between 0 and 1, characterizes the degree of orderliness or organization in eye movements, by considering how predictive a current fixation is of the immediately subsequent fixation. In the case of more explorative eye movements (corresponding to higher entropy values), knowledge of the current fixation provides little information on the probably location of the next fixation. In more constrained eye movements (corresponding to lower entropy values), there are greater probabilities of predicting the location of the next fixation given knowledge a current fixation. In other words, entropy captures the degree of constraint between pairs of transitions. The lower the entropy, the more predictable the transitions; the higher the entropy, the less constrained and more exploratory the eye movements.

The relationship between entropy and memory was demonstrated by Althoff and colleagues (Althoff & Cohen, 1999). In their study, participants viewed famous versus novel faces. Famous faces differ from novel faces only in prior memory, not visual complexity; therefore, any differences observed in eye movements between these stimuli are attributable to memory. The study found that higher entropy was associated with the viewing of familiar faces compared to viewing of novel faces. Researchers posited that viewing of novel materials encourages more constrained, stereotypical viewing to extract maximum amounts of information, whereas viewing of materials with memory need not require such constraint and supported the ability for greater explorative eye movements. Applying these findings to the current experiment, we would predict eye movement entropy to differ between the experimental and control conditions, should relational stability imparts context-like benefits to memory.

Results & Discussion

Analysis 1: Items vs. Relations Memory between Experimental and Control Conditions

Our first investigation into the impact of stability on memory was to summarize the average proportion of item and relation components correctly reconstructed per trial, comparing the experimental (BVfirst, ISfirst, BVsecond, ISsecond) to the control conditions (BfirstControl, IfirstControl). Furthermore, we distinguished between stimulus domains—images versus screen locations—of the item or relational information examined. Specifically, we summarized stimulus item performance (B, B, and I, I) separately from location item performance (V, V, and S, S), and item-item relations (B-I) performance separately from stimulus-location relations (B-V and

I-S). Importantly, we restricted analyses of the relations to trials where at least 3 stimulus items were correctly chosen. This restriction ensured that relations performance was summarized independently of the stimulus item memory. In other words, the incorrect relations reported here indicate a true lack of relational memory and exclude contributions from item memory.

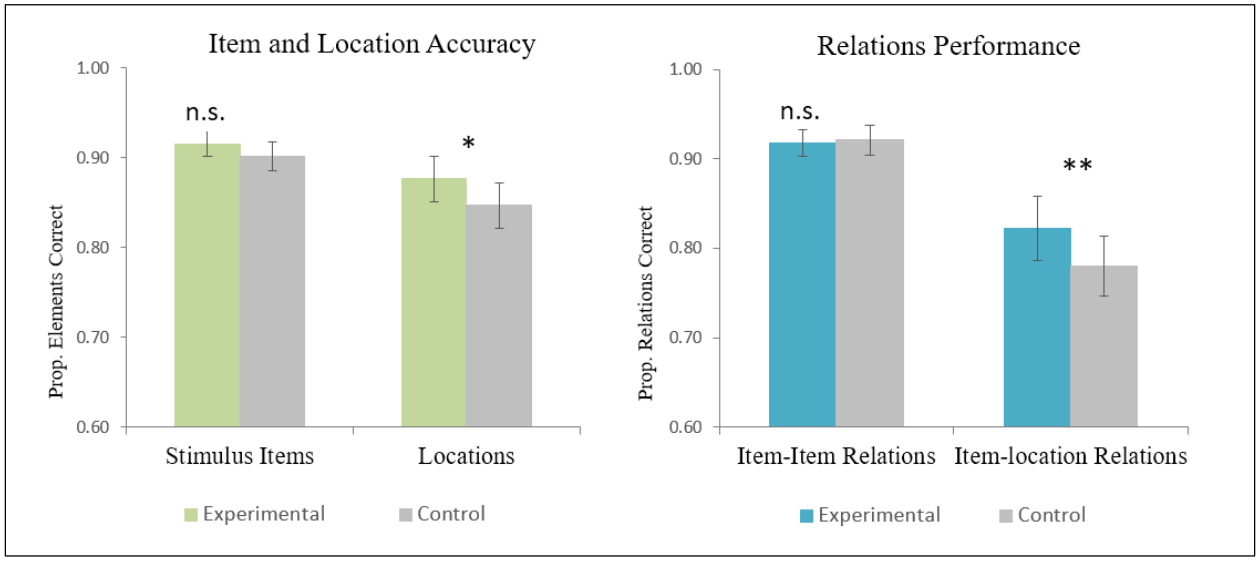


Figure 4.3: Effects of stability on item memory, location memory, and relations memory for stimuli and locations. Relations memory accuracy was conditioned upon trial where at least 3 items were correctly selected (*denotes significance at $p < .05$, ** at $p < .01$, *n.s.*is not significant).

As shown in Figure 4.3, this analysis yielded a dissociation in terms of the influence of stability on memory. Stability did no impact the ability to recall the stimulus items shown in a given study trial. Item memory performance was not significantly different between stable conditions and control conditions, t (28) = 1.603, p =.12. Similarly, stability did not significantly impact participants' ability to reconstruct the studied item-item pairs, t (28) = -0.364, p =.719. The impact of stability was detected in location-related accuracy performances. The ability to reconstruct location information, by putting some stimuli in a screen quadrant that was occupied during study, was significantly better when stability manipulation was present, such as in the

experimental conditions, t (28) = 2.67, p = .012. Similarly, participants were significantly better at reconstructing item-location relations in experimental blocks compared to control blocks, t (28) = 3.31, p < .002.

The result that context-like stability impacts stimulus and location information differently is an interesting finding that makes contact with previous evidence of a componential view of episodic memory. Specifically, established research showed that different subregions within the medial temporal memory regions, namely the perirhinal and parahippocampal cortices, provide inputs to the hippocampus in support of episodic memory processing (for reviews, see Diana et al., 2007; Eichenbaum et al., 2007). These subregions have been shown to be differentially sensitive to object versus scene information (Staresina & Davachi, 2010; Staresina et al., 2011). Thus, such componential views of episodic memory provide a plausible mechanism to explain how context-like relational stability can affect item versus relations aspects memory differently.

In terms of why location memory and item-location relations memory were specifically sensitive to the stability manipulation, there are several possible explanatory factors that warrant further research to adjudicate between them. First, it may be that the high degree of recall accuracy obscured effects of stability on stimulus memory performance. It remains to be tested whether relational stability may impact the recall of stimulus memory if future studies could be modified to yield lower memory performance for these components. Second, it may be that location information and item-location relations were the only measures impacted because the stability manipulation was operationalized via stable mappings of items in their locations. Future investigations should explore whether the other types of stability, such as item-item or location-location stability, also uniquely benefit location and item-location memory or if there exists an

interaction between the components of episodic memory affected and stimulus domain involved in instantiating such stability.

One thing to note in the interpretation of the present results is that measures shown to be impacted by stability, namely location information and item-location relations, are not independent of each other. By nature of it being one part of the item-location relations measure, some proportion of the location performance must necessarily be redundant with correct item-location performance. On the other hand, the item-location relations performance can only arise from accurate memory of the tested item-location relation. In this way, we find the item-location relations to be a cleaner measure of performance and we therefore focus further analyses of stability effects on memory restricted to the item-location relations measure.

Analysis 2: Stable versus Unstable Information Performance

Given the observation from analysis 1 that item-location relations memory was significantly impacted by the presence of stability, we further investigated whether stability enhanced memory for all item-location relations in such experimental blocks or whether memory benefit was limited to the stable relations. Thus, we examined item-location relations accuracy within blocks separately for stable, unstable, and control relations. Performance was separately calculated for stable relations (stable B-V and stable I-S) versus the trial-specific portion of item-location information in each trial, in the experimental conditions (unstable B-V and unstable I-S) and was compared to performance of all item-location relations in the control conditions. All relations included in this analysis were only from trials where the correct stimulus items were first selected, so that the results presented here could not be driven by any item memory differences.

Furthermore, we examined these dependent measures as a time course across the 18 iterations each of the test trials within each experimental block. Given that relational stability was a property that could only emerge across repetitions of trials, adopting this time course analysis allowed us to ascertain two stability-related memory phenomenon—first, we could observe whether stability benefited memory for the stable relations across study repetitions, and second, we could determine whether memory performance for unstable items benefited from the presence of stability as the trials progressed.

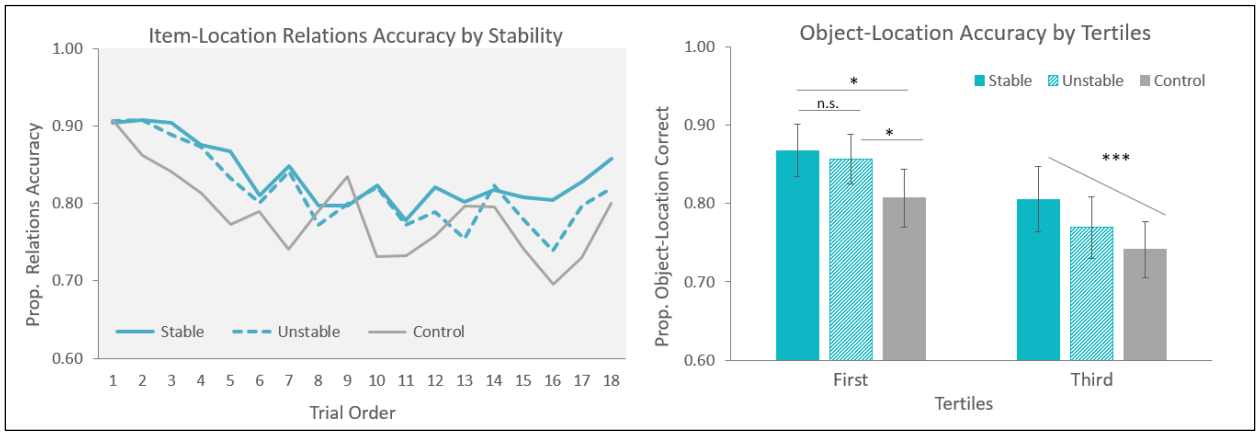


Figure 4.4: Memory accuracy for item-location relations by stable, unstable, or control relations (conditioned upon corrected selected items), averaged across 18 iterations of trials with the same stimulus set per block. On the right, is the data summarize in tertiles and tested for differences between the conditions in each tertile (*denotes significance at p <.05, ** at p <.01, *** at p < .001, n.s. is not significant).

As can be seen form Figure 4.4, the average level of item-location performance in stable blocks distinguished from that in the control blocks throughout the majority of the trials in a block. Interestingly, memory for stable and non-stable relations within an average experimental block were initially similar but become more divergent towards the end of a block. To summarize and test for this pattern of results, we summarized the time course data by tertiles (1st tertile contains trial iterations 2 to 7, 3rd tertile contains trial iterations 13 through 18).

Trend analyses were conducted for each tertile. For the 1st tertile, results showed a close to significant quadratic trend (p =.055). Follow up t-tests revealed differences between the item-location relations form experimental blocks and those from the control blocks. With respect to the 3rd tertile, a significant linear trend was found across the stable, unstable, and control item-location relations performance (p =.001).

Thus, analysis of item-location relations confirmed the efficacy of the stability manipulation. Memory for stable item-locations were initially similar to those of the non-stable item-locations, but as the trial repetitions progressed, the stable relations performance was higher than the unstable relations form the same trial, as demonstrated by the significant linear trend in the 3rd tertile. Also importantly, both stable and unstable item-location relations from experimental blocks, still out-performed those from control conditions, supporting the idea the presence of stability, perhaps acting context, helps in episodic memory performance.

Partitioning trial information into stable, or more context-like, information versus trial-specific information is a distinction commonly assumed by experimental designs (for review , see Yonelinas, 2002). A critical difference between this analysis and analysis 1 exists in that information was distinguished here based on its stability status.

Examining accuracy for stable versus unstable, trial-specific information allowed for the exploration of two different issues. First, by analyzing memory performance on the stable information, we established that stability information conveyed across multiple trial repetitions translated into better memory for such relations themselves. Research on context facilitating memory typically focuses on the to-be-remembered items only, and few paradigms affords the opportunity to examined memory for the contexts themselves, as we have done here.

Second, we examined memory for unstable item-location relations from trials in experimental conditions and observed memory benefits over those in trials from the control conditions. Thus, memory performance of the unstable, trial-specific portions of the trials benefited from the presence of stable relations in the trials. We argue, this may be considered an instance of context facilitation and supports our hypothesis that relational stability imparts context-like affects in memory.

Analysis 3: Presentation Order and Stimulus Size Interactions with Stability

After observing the differential effects of stability on item and relations performance, we further examined whether stimulus properties such as order of presentation of the stable information, and the size (background or inset) of the stimulus involved in conveying context impacted memory outcomes.

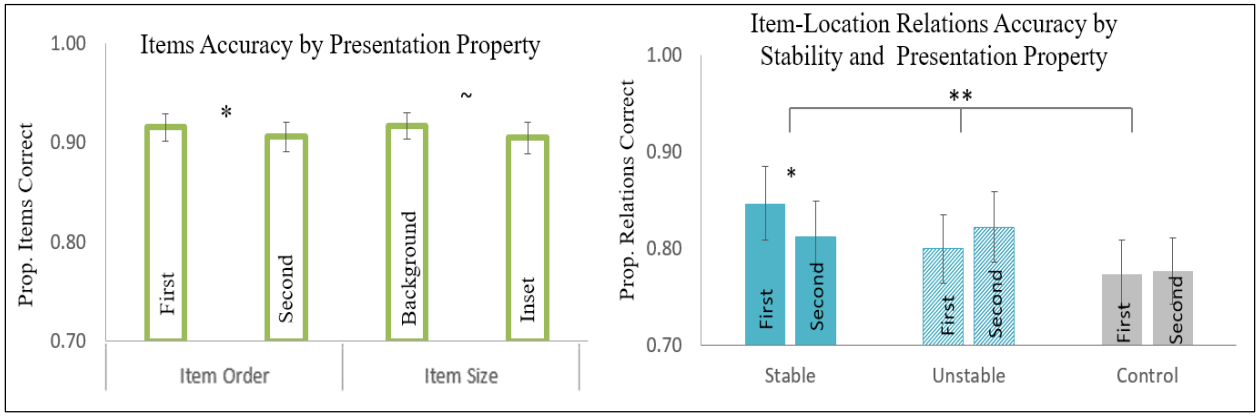


Figure 4.5: Stimulus properties (temporal order or stimulus size) and the effects of stability on item versus relations memory (*denotes significance at p <.05, ** at p <.01, *** at p < .001, ~ denotes marginal significance at p = .073).

In terms of memory for items, as shown in Figure 4.5, items presented first in a given quadrant enjoyed better memory performance than those that were presented second. Using a 3-way ANOVA with factors of Stability, presentation order, stimulus size, a significant main effect

of item order was revealed, F (1,28) = 9.48, p =.005. There is also a marginal effect of item size, with background items having numerically higher accuracy than inset items, F (1, 28) = 3.46, p =.073. However, there was no significant main effect of stability for item memory, F (1.02, 33.86) = 2.36, p =.13. This is consistent with the pattern of results shown in analysis 1.

In terms of memory for relations, again, the main effect of stability as established in analysis 1 was confirmed by the 3-way ANOVA. Recall of item-location relations (both stable and unstable) from experimental conditions were significantly better than those from control conditions. An interaction between stability and order was also revealed (p = .048). Subsequent simple main effects analysis reveal that stable information which appeared first in a quadrant yielded better memory performance than those that appeared second (difference =0.034, p =.028).

All in all, results from analysis 3 suggest that the order of presentation has an impact on memory. Being first experienced in a quadrant provided benefits in recall of the stimulus item that was associated with that particular location. Furthermore, the interaction of stability and order information suggests that context-like information when experienced first, also yields better memory for the context itself.

Due to the novelty of the current experimental question, the result that being perceived first interacts with stability to yield better memory is also novel and one that has not been directed tested in previous research. However, if we accept that relational stability acts in a context-like manner, this finding would suggest there is something about being perceived first that further reinforces context information. This interpretation makes good contact with the types of context information that is typically present in day-to-day experiences. In everyday life, we often have access to context information prior to experiencing event-specific, item information.

For example, we tend to perceive location contexts (a building, a room) before we experience what is taking place in the location; we tend to know what situation to expect (a birthday party, a work meeting) before the events themselves unfold. Thus, the current finding of an interaction between stability context and presentation order suggests that context may be defined by relational stability but there are stimulus properties such as "firstness" that is common in everyday experiences with context information that may further bias and affect context processing and its effects on memory.

Analysis 4: Eye Movement Entropy between Experimental and Control Conditions

Entropy analysis, as an index of memory, was especially informative in examining eye movements during test trials in the current paradigm compared to other methods of summarizing eye movements.

We restricted entropy calculations to only those trials where all component item and relations were correctly reconstructed (in other words, trials with 100% accuracy). This was so that eye movements engendered by non-memory processes, such as response planning and execution that allowed participants to use the mouse cursor to navigate around the test display, would be equalized. This also made for a good measure of how stability influenced the underlying *organization* of memory representations, while controlling for differences in overt memory performance. If differences in entropy were observed between experimental and control conditions despite equal overt memory, we could infer that they were supported by different underlying memory representations, and that such a difference was related to the presence or absence of stability.

A paired *t* test comparing the entropy measure obtained from correct trials revealed significantly greater entropy in the experimental conditions compared to the control conditions, $t(28) = 2.41$, $p = .023$ (experimental $M = 0.26$, *SE = 0.07;* control $M = 0.25$, *SE = 0.06*). The number of meaningful transitions between the 16 pre-defined ROI's that informed the entropy measure also differed significantly between the conditions, $t(28) = 2.20$, $p = .036$, with the experimental conditions having greater numbers of meaningful transitions ($M = 21.03$, $SE = .74$) than the control conditions ($M = 20.24$, $SE = .72$).

We also analyzed and examined study trial eye movements. However, data from this time period proved to be undiagnostic of later memory performance. The inclusion of a sequential presentation of trial stimuli strongly guided visual sampling patterns during study trials. Eye sampling was almost exclusively restricted to occupied screen quadrants, and followed the order of trial stimuli presentation. In this sense, the average entropy of all study trials was effectively zero, signifying extremely constrained eye movements following the presentation order of each given study display.

In summary, results from the entropy analysis appeared consistent with our hypothesis that the presence of stable relations influenced memory organization of the study events. The pattern of higher entropy associated with stable conditions compared to control conditions makes contact with the finding established by Althoff and Cohen (1999). In their study, researchers showed that viewing behavior during recognition of face stimuli with prior memory had higher entropy (less constrained viewing) compared to those that were novel. The researches attributed lower entropy (or more constrained viewing patterns) to attempts at more efficiently acquiring information from novel stimuli. In contrast, stimuli with greater amounts of prior memory may free up resources for more unconstrained and non-stereotypical visual sampling of the presented

information, resulting in higher entropy values. We believe the same interpretation aptly applies to results from the current experiment. The presence of relational stability facilitated memory organization, leading to better quality or great amounts of memory compared to instances without stability structure, even under conditions of equal overt reconstruction accuracy. Better underlying memory representation in the experimental conditions, in turn, is expressed in more unconstrained eye movements. Furthermore, we propose that the influence of stability on memory organization may have by stable relations acting on memory processing in a context-like capacity. Contextual influence on memory organization has been demonstrated directly in rodent neuronal recordings(McKenzie et al., 2014). Neural firing patterns have been demonstrated to be more similar across different experimental features (such as location and reward value) within the same context than firing patterns to the same feature that were presented across contexts, suggesting context information organizes the other event features occurring within it.

General Conclusion and Future Directions

This study tested the novel hypothesis that stability of interrelationships between a subset of components within a memory episode is the information property that leads those components to be processed as context. We operationalized this relational stability as constant mappings of certain objects to their presented screen locations, across multiple study repetitions. Additionally, we incorporated different stimulus presentation orders (such as presenting stable relations first or second) and different sizes of objects (such that stable items may be in the background or as the central element) to explore how these stimulus properties, commonly associated with everyday

context information, may interact with our hypothesized information property of context as relational stability.

Confirmatory evidence of our hypothesis would consist of better memory performance in conditions with such item-location relational stability compared to conditions without. We also collected eye movement data to detect possible differences in underlying memory representations as indexed by the degree of eye movement organization during memory retrieval.

Overall, we believe the results for the current study show support for our hypothesis. We observed facilitation of reconstruction memory for item-location relations in conditions with stability context compared to conditions without, as reported in analysis 1. We additionally demonstrated, in analysis 2, that the memory benefit of stability extended to all components within a memory episode. As exposure to the stable components increased, memory for the unstable components also increased. In analysis 3, we reported perceptual properties commonly associated with context interacted with stability to result in additional facilitations in memory performance. Stable information perceived prior to exposure to unstable, trial-specific information had better recall accuracy than those that were presented after the unstable information. Lastly, in analysis 4, we provided evidence that context-like stability manipulation may alter memory organization. We showed that even at comparable levels of overt memory performance, the presence of stability was associated with less constrained viewing patterns compared conditions without stability.

In summary, the current study provides good evidence that stability of relational information plays a major role in determining context. As a first study into this avenue of research, stability was singularly operationalized through item-location relations. To ascertain the generalizability of the current results across stimulus domains, future studies should implement test for memory performance when stability is conveyed through types of relations, such as item-

item relationships. A real-world example of this would be the context “dancing” which would be defined by the co-presence of 2 people, not their relationship to particular locations. If stability also impart memory benefits when implemented other types of relations, it would constitute strong support for the fundamental role relational stability plays in determining context.

One limitation to the current design is the complexity of the stimulus onsets and reconstruction at study and test portions of the experiment. These design features necessitated eye movements be summarized in a more data-driven manner, such as via entropy calculations. Future studies may take advantage of many other eye movement measures (Hannula et al., 2010) by enforcing a delay period at reconstruction, such that eye movements may precede behavior responding and stand to provide even more nuanced information about the retrieval process of memories encoded with or without the presence of stability context.

CHAPTER 5: GENERAL DISCUSSION

In a collection of three experiments, this dissertation examined the sensitivity of relational memory representations to the factors of repetition, negative emotion, and presence of context information. Even though the factors were tested in separate experiments and cast as 3 different questions, this chapter aims to synthesize the findings and argue that the factors tested across three experiments could all be viewed as various forms and facets of context information and its influence on relational memory. We will begin by briefly summarizing findings from each study and highlight the novel contribution(s) each experiment imparts to the understanding of relational memory representations and the field of episodic memory. We will then present arguments on how each study can be considered a type of test on the effects of context on relational memory.

In Chapter 2, we investigated the neural substrates of item versus item-in-context or relational information. Study utilized a novel design to objectively and experimentally control for the amount of item versus context information to be encoded. This was achieved through the use of spaced-repetitions at study. In cognitive models memory, spaced repetitions at encoding has been postulated to increase item memory via increasing context information (Malmberg & Shiffrin, 2005; Malmberg, 2008). Therefore, a note-worthy finding from Chapter 2 consisted of the successful manipulation of memory strength via repetition, as indexed by increasing accuracy across conditions with greater numbers of study repetitions. Additionally, this study extended empirical evidence on the effects of spaced repetitions on context by explicitly, and experimentally defining what was item and what was context (by the usage of face-scene paired stimuli). The employment of experimentally specified context information eliminated the need to invoke the idea of context or to infer the degree of context change, as have been done in some

studies using only item stimuli, as an explanatory variable in explaining item memory differences between spaced or massed repetitions conditions (Malmberg & Shiffrin, 2005; Shiffrin, Ratcliff, & Clark, 1990).

The study in Chapter 2 also provided pivotal novel evidence that there were graded neural responses in memory regions to parametrically varying degrees of item-in-context or relational information, dissociated from strength of item memory. The finding is of especial importance as such parametric modulations were found in the hippocampus – established to be the seat of relational processing and representations (Cohen et al., 1999). Graded activation to varying degrees of relational information has not yet been demonstrated in a long-term memory paradigm such as tested in Chapter 2. Additionally, the fact that activation in this region was selective to changes in relational information but not item information provides strong support that episodic memory representation consists of multiple streams of information, not least, that of item and relational information. In this way, this contributes to our understanding of the underling organization of episodic memory.

In terms of viewing the results of Chapter 2 with respect to the study of context, there is a straightforward relationship. For one, the experiment contained a clear, task-defined context component by using scene stimuli, which is canonically considered to be context (Hayes et al., 2007), and presented them as backgrounds to the superimposed face stimuli which further reinforced the scenes as context information. Additionally, such item-context face-scene pairs were presented across multiple repetitions. Spaced repetitions in themselves have been postulated to increase context accumulation (Malmberg & Shiffrin, 2005). By using the conjunction of scene stimuli and spaced repetitions, Chapter 2 constituted an experiment that strongly examined the effects of context on episodic memory.

In Chapter 3, the experiment examined the effects of negative emotion on relational memory representations, tested through recognition memory of face-scene pairs. A manipulation of repetition was also implemented.

A first, notable contribution to the understanding of emotion and memory was to test the effects of negative emotion on relational memory directly, rather than on memory for components parts of episodic memory separately. Previous investigations tended to focus on testing for emotion effects on item and context or source information separately, without testing the possibility that relational binding may itself be affected (for a review, see Chiu, Dolcos, Gonsalves, & Cohen, 2013). Results from this study highlighted possible changes to relational memory by negative emotion, detected in more nuanced and fine-grained measures of behavior such as response time and eye movement data analyses.

Furthermore, the use of eye movement monitoring provided the opportunity to assess whether attention biasing effects of emotion, which is a dominant theory on the effects of emotion on memory (Kensinger et al., 2007), played a role in the memory outcome of the experiment. Notably, results in Chapter 3 revealed evidence that while negative stimuli indeed influenced attention distribution, such attention allocation changes did not relate to relational memory outcomes. In addition, eye movement results revealed negative emotion may modulate the underlying organization of relational memory, as demonstrated through greater visual sampling in the negative emotion condition during encoding compared to the neutral condition, within trials with equal explicit recognition accuracy.

The experiment in Chapter 3 contributes to the understanding of context and relational memory in the sense that emotional value maybe considered a context feature, rather than a separate influence. Specifically, as outlined in relational memory theory (Cohen et al., 1997;

Eichenbaum & Cohen, 2001), hippocampal-dependent relational processing is not restricted to specific modalities, nor to external or internal sources, of information. In this way, emotional stimuli constitute a feature of context that may be processed and bound via relational processing into the representation of episodic memories, similarly with other stimulus features. Indeed, previous studies have demonstrated hippocampal sensitivity to the emotional materials such that greater hippocampal activation was observed during encoding of emotional stimuli compared to neutral stimuli (Kensinger & Corkin, 2004).

In Chapter 4, we tested a novel hypothesis not before examined that context is composed of event components that have stable, or consistent relational information across multiple encounters or memory episodes. In this way, the notable contribution to the study of context and episodic memory processing made by this chapter is the attempt to unravel the underlying information properties or processing characteristics of context information.

Implied by our hypothesis that context consists of relational stability is also the idea that context information is not determined by specific stimulus modalities such as scene information. While other studies have endeavored to dissociate context from particular stimulus modalities, such as demonstrating neural response to differential amounts of context information given the same degree or scene information (Bar et al., 2008), they have not explicitly put forward alternative definitions of context information beyond scene information. To this end, we believe the experiment in Chapter 4 was the first to propose and test an operationalization of context that is an information property, or processing characteristic—namely, that context is may be defined by relational stability across encounters.

Results from Chapter 4 showed support for our novel hypothesis and operationalization that context could be defined by stable relational information. Evidence of episodic memory

facilitation was observed in memories for events with stability structure compared to memories for events without. Specifically, the presence of constant item-location mappings across repetitions improved memory for all item-location relational information within events, compared to memory for those relations within events without stability structure. Importantly, further analyses revealed that improved item-location memory was for both the context-like stable features, as well as for item-like trial specific information. Thus, a context facilitation-like benefit to memory was observed. Eye movement measures also indicated greater memory (or familiarity) for episodes studied with stability structure, as evidenced through more exploratory eye movements during reconstruction for events with stability, compared to events without, within trials of equal accuracy.

Taken together, findings form the 3 experiments contribute to the endeavor of characterizing the factors that influence the processing and representation of relational information which underpins episodic memory function. They have provided evidence that relational memory representations are not all "created equal" but, instead, may have different degrees of underlying strength, as can established through repeated exposure (Chapter 2), may be weakened by negative emotion (Chapter 3), or may be organized differently as influenced by the presence of stability in the relational information acting in a context-like manner (Chapter 4).

Lastly, in this chapter, we further argued that the 3 factors tested in this dissertation may all fall within the often-evoked but yet ill-defined concept of "context" information. Therefore, a fruitful avenue for future studies would be to focus on further uncovering and refining information and processing properties related to context information, examine its interactions with relational memory representations, in order to arrive at even more nuanced understanding of episodic memory.

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