Bachelor Degree Project

AROUSAL-INDUCED MEMORY AUGMENTATION

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Abstract

Emotional events are often better preserved in memory than events without an emotional component. Emotional stimuli benefit from capturing and holding the attention of a perceiver to a higher degree than more emotion-neutral stimuli. Arousal associated with experiencing emotionally valenced stimuli or situations affects every major stage in creating, maintaining and retrieving lasting memories. Presented in this thesis were models delineating the behavioral and neurological mechanisms that might explain arousal-induced effects on subsequent memory outcome. Based on a study of relevant literature, findings were presented in this thesis that highlight amygdala activation as crucial for the enhancement of memory generally associated with emotional arousal. The amygdala modulates processing in other areas of the brain involved in memory. Heightened levels of norepinephrine, stemming from sympathetic nervous system activation, underlies observable arousal-induced memory effects and seem to be a crucial component in enabling glucocorticoid augmentation of memory. Arousal seems to further amplify the biased competition between stimuli that favors the neural representation of motivationally relevant stimuli and stimuli of a sensory salient nature. The aim of this thesis was to outline the impact of emotional arousal on different stages of memory processing, including processes for memory formation, strengthening of memory traces, and eventual subsequent retrieval.

Keywords: arousal, memory, biased competition, consolidation, norepinephrine

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Introduction

Memories are far from equally durable, some may persist for a lifetime while others are as fleeting as mist, barely outliving the subjective experiences that were their maker. They vary on a continuum of strength, vividness, accuracy and the level of confidence one puts in them. Memories of emotional events are often well preserved for long periods of time, in relation to memories of neutral events that often fade from awareness and are quickly forgotten. The reason for this appears to be that emotion influences information processing at multiple stages and in multiple memory systems. Results of memory research demonstrate that emotional and non-emotional information diverges in how efficiently it is detected, the duration in which it stays the focus of attention, how long it is retained, and the likelihood of later successful retrieval of the information (Levine, & Edelstein, 2009).

A memory advantage for events that triggered an emotional reaction makes sense from an evolutionary perspective. Whether it be an occurrence of a positive nature, such as finding a tree ripe with fruits, or an aversive experience like witnessing someone getting bit by a snake, remembrance of such events clearly have adaptive value in helping an individual to navigate a perilous environment and guiding future behavior. Emotional stimuli, whether pleasant or aversive are in such a context generally more important than neutral stimuli for reproductive success.

A variety of emotional as well as cognitive challenges may trigger autonomic arousal, affecting heart rate, pupil dilation, galvanic skin response, in addition to increasing levels of various stress hormones such as epinephrine and cortisol (Mather, & Sutherland, 2011). Even a simple stimulus, such as an emotional picture shown briefly may increase autonomic arousal (Bradley, Miccoli, Escrig, & Lang, 2008). When we are subjected to an arousing situation, for example stress, an array of hormones, peptides and neurotransmitters are released throughout the body as a consequence of certain brain processes being instigated,

all of which are aimed at helping us handle the immediate arousing situation and later, restore homeostasis (Schwabe, Joëls, Roozendaal, Wolf, & Oitzl, 2012). Two systems are particularly involved in the stress response; the fast acting sympathetic nervous system and the slow hypothalamus-pituitary-adrenal (HPA) axis (Joëls, & Baram, 2009). When arousal is mentioned in the context of this text, even though it pertains to an emotional state, it usually equates to a physical state that involves the at least partial activation of the sympathetic nervous system and/or the HPA-axis. Activation of the HPA-axis leads to the release of glucocorticoids from the adrenal cortex (mainly cortisol in humans, corticosterone in rodents) and sympathetic nervous system reactions include the release of the catecholamines epinephrine and norepinephrine (Schwabe et al., 2012). When something is experienced as arousing, the sensory information related to that event, be it nociceptive, visual or auditory, is processed in the corresponding brain regions and is then projected to the hypothalamus. Activation of the paraventricular nucleus of the hypothalamus instigates secretion of corticotropin-releasing hormone (CRH) and vasopressin. From the hypothalamus, neurons in the brain stem are activated that subsequently activities the sympathetic nervous system (Joëls, Fernandez, & Roozendaal, 2011). Activation of the sympathetic nervous system instigates responses that include the release of the epinephrine (EPI) and norepinephrine (NE) from the adrenal medulla (Joëls, & Baram, 2009). These hormones are also released in limbic structures such as the amygdala and hippocampus, via the vagal nerve and the nucleus tractus solitarius (NTS), and more directly by activation of noradrenergic cells in the locus coeruleus (LC) (Krugers, Karst, & Joels, 2012). As an outcome of these pathways, shortly after the onset of stress, the neurons in the amygdala are subjected to high levels of NE. As a consequence of the increase of CRH and vasopressin in the pituitary glands, another hormone, adrenocorticotropin (ACTH), is also released in circulation. Exposure to ACTH in the adrenal cortex increases the synthesis and release of corticosteroid hormones (Joëls, et al., 2011;

Joëls, & Baram, 2009). These hormones are very lipophilic and easily pass the blood-brain barrier and bind to cells carrying corticosteroid receptors. There are two types of receptors that binds corticosteroid hormones; mineralocorticoid receptors (MRs) and glucocorticoid receptors (GRs). MRs has much higher affinity for the ligands corticosterone, cortisol, and aldosterone than GRs, which means that in humans MRs are substantially activated even when cortisol are at base level while GRs are not activated at basal concentrations. However, when a stressful or arousing experience triggers activation of the HPA-axis, cortisol production is dramatically increased, leading to concentrations high enough to activate the GRs (Krugers et al., 2012).

Two methods that, in combination, are useful for investigating correlations between brain activity and memory are event-related designs and the so-called subsequent memory paradigm. Event-related designs is a technique used in fMRI studies that enables detection of changes in the blood oxygen level dependent (BOLD) hemodynamic response to neural activity on a stimulus-by stimulus basis so that neural activity in response to specific events can be identified (Liu, 2012). This type of design has proven a valuable tool in investigating the neural correlates of memory processes, as it allows for establishing a direct link between memory performance and brain activity for specific items. The subsequent memory paradigm, in which comparisons between brain activity for subsequently remembered and forgotten items can be made both during the initial encoding phase and later during the retrieval phase, is frequently used in combination with event-related designs. By assessing activity recorded during encoding and linking this to subsequently remembered vs. forgotten items, it is possible to calculate the so-called *difference in memory effect*. Brain regions that exhibit greater encoding activity for remembered than for forgotten items and regions in which activity results in more items being remembered than forgotten are assumed to be involved in successful memory encoding. Likewise, by comparing activity between

remembered and forgotten items during retrieval, regions that show greater activity for successfully retrieved items than for items that were not retrieved can be identified. By contrasting recorded activity in a manipulated condition that includes an emotional component with a control condition, it is thus possible to pinpoint regions whose memory-related activity during encoding and retrieval is receptive to emotional modulation. Thus, event-related designs and SMP enables researchers to identify regions of the brain that during different stages of memory processing display an interaction between memory and emotion in individual participants (Liu, 2012).

The amygdala (AMY) consists of an almond-shaped group of nuclei located within the MTL. AMY has been extensively emphasized as playing a crucial role in emotion-induced memory enhancement, from encoding (Kensinger, & Schacter, 2006) to consolidation (Ritchey, Dolcos, & Cabeza, 2008), and later retrieval (Sergerie, Lepage, & Armony, 2006). There are several studies that have reported that the correlation between activation in the amygdala and the medial temporal lobes (MTL) as well as activation in the amygdala itself are associated with successful encoding of emotional information in relation to neutral stimuli (e.g., Dolcos, Denkova, & Dolcos, 2012).

Findings concerning how arousal affects memory often are inconsistent and sometimes show opposite patterns. Arousal has been found to enhance memory for central details of an event at the expense of peripheral details. This has been interpreted indicating arousal as having a narrowing effect on memory (Mather, & Sutherland, 2011). On the other hand, in some instances, emotion and related arousal enhances memory for seemingly peripheral details as well (Laney, Campbell, Heuer, & Reisberg, 2004). Additionally, in some cases, intense emotion impair memory for central and potentially important information (Morgan et al., 2004). Further, while some studies have found that emotional arousal enhances memory for gist information but not details (Bookbinder, & Brainerd, 2017), other

results seem to indicate that there is an emotional enhancement of memory for specific details of emotional objects as compared to neutral content (Kensinger, Garoff-Eaton, & Schacter, 2006). In addition, arousal can lead to both retrograde amnesia and retrograde enhancement of memory (Knight, & Mather, 2009). Some studies found post-encoding arousal to act more as a memory enhancement agent of emotional information than neutral information (Buchanan, & Lovallo, 2001), indicating that arousal enhances memory consolidation for emotional information. All the while other studies found that arousal experienced post-encoding of neutral information indeed can enhance memory of that neutral stimuli, indicating a wider memory consolidation enhancement, including that of neutral information (Knight, & Mather, 2009; Nielson, & Powless, 2007).

The modulation model highlights the amygdala as a modulator, enhancing processing in various other memory-related areas of the brain via noradrenergic mechanisms, leading to a strengthening of memory traces and subsequent enhanced consolidation of emotional material and events. There is ample evidence in the literature that the amygdala activation modulates memory consolidation (e.g., Chavez, McGaugh, & Weinberger, 2013; Roozendaal, Castello, Vedana, Barsegyan, & McGaugh, 2008; Roozendaal, & McGaugh, 2011). However, long-term memory consolidation takes hours or even days, but subsequent memory effects in the amygdala can be found even when memory testing is conducted within minutes of initial encoding (Talmi, 2013). The modulation model fails to explain the finding that emotional arousal sometimes enhances memory for neutral stimuli. Furthermore, the modulation model does not provide an explanation for the effect of emotional stimuli on early long-term memory. As the consolidation of memory traces takes time, the influence of arousal on consolidation processes should not manifest and cannot adequately explain the observable arousal-effects on subsequent memory found when testing in close temporal proximity to

exposure to emotional stimuli. Nor is the modulation model sufficient to explain the immediate effects of arousal on encoding-relevant perceptual and cognitive processes.

The ABC model and GANE model aim to bridge these gaps and complements the modulation model by accounting for these effects. According to the arousal-biased competition (ABC) model (Mather, & Sutherland, 2011), arousal (whether emanating from internal thoughts, stress, hormones, or external stimuli) strengthens memory for items that are most prominent in the competition for selective attention. This contest among stimuli begins already during perception and continues as a contest for mental representation into long-term memory consolidation. Arousal is thought to bias perception and attention towards the most distinct or motivational-relevant stimuli, and then enhance memory consolidation for these stimuli, whether or not those stimuli are arousing in themselves. However, the ABC model fails to clarify what mechanisms in the brain are involved in amplifying the effect of priority due to arousal. The newly formulated glutamate amplifies nor-adrenergic effects (GANE) model may delineate possible mechanisms explaining these effects, emphasizing glutamate interactions with norepinephrine as critical for inducing the activation difference between high- and low-priority neural representations. The GANE model provides a possible complementary account of how arousal may have immediate effects on perception, attention, and the activation difference between high- and low-priority neural representations, affecting both early- and late long-term memory.

This thesis will primarily focus on the impact of emotion and arousal on explicit (declarative) memory. Declarative memory refers to the capacity to consciously remember past experiences, facts, and concepts and is distinct from procedural (non-declarative) memories in that they can be verbalized (Miendlarzewska, Bavelier, & Schwartz, 2016). The medial temporal lobe (MTL) system consisting of the hippocampus, dentate gyrus, subicular complex, perirhinal cortex, entorhinal cortex and parahippocampal cortex, has been firmly

established as necessary for the formation, consolidation, and retrieval of declarative memories (Dolcos, & Denkova, 2008; Miendlarzewska et al., 2016). The aim of this thesis is to outline the impact of emotional arousal on different stages of memory processing, including processes for memory formation, strengthening of memory traces, and eventual subsequent retrieval. Observable behavioral effects of emotion on such processes in human subjects will be integrated with findings from animal studies in an attempt to explain data from a neuroscientific point of view. This thesis will generally be disposed in line with the course in which a memory is created, starting with arousal effects on the attention and perception necessary for successful encoding. This will be followed by an account of noradrenergic mechanisms involved in the consolidation process, and a briefer account of arousal-induced effects on retrieval performance. Findings will be discussed on the basis of the ABC, Modulation, and GANE models in an attempt to delineate the sometimes inconsistent and contradictory findings found within this field of research.

Biased Competition

Our lives are filled with situations in which countless stimuli compete for our attention. The capacity of our brain to prioritize information according to motivational relevance allows us to take action without being overwhelmed by extraneous distracting details. Two processes are active simultaneously, bottom-up processing and top-down processing (Mather, & Sutherland, 2011). The top-down process is guided by prior knowledge, context, and motivational goals, while the bottom-up process relies primarily on sensory information from the environment. Both processes can bias our attention in a particular direction (Beck & Kastner, 2009).

The biased competition theory of selective attention proposes three general principles (Mather, & Sutherland, 2011). First, visual processing is competitive. Within each

system involved in the processing of visual information (sensory and motor, cortical and subcortical), there is limited capacity for representation, so the strengthening of a particular visual objects' neural representation comes at the expense of the representations of other objects. Secondly, top-down and bottom-up processes bias attention among multiple objects, helping to resolve the competition. Thirdly, the competition is integrated across brain systems, so that a dominating visual object within one system, likely will gain dominance in other systems as well, such as higher-order prefrontal and parietal cortices (Beck & Kastner, 2009).

During directed attention neural signaling increases in the frontoparietal attentional network, which in a top-down fashion modulates activity in sensory brain systems (Mather, & Sutherland, 2011). Directing attention toward a specific object among others decreases the quelling effects of the other competing objects. For example, one fMRI study had participants watching pictures of a face and a scene adjacent to each other on a screen (Johnson & Johnson, 2009). When the pictures no longer could be seen they were asked to think about one of the pictures. In comparison to a control condition in which the participants were not asked to think about either picture, thinking about the face suppressed activity in the parahippocampal place area, an area implicated in the processing of scenes (Rajimehr, Devaney, Bilenko, Young, & Tootell, 2011), while thinking about the picture of the scene increased activity in the parahippocampal place area. This indicates that top-down priorities can bias the contest among mental representations even without the immediate presence of external perceptual stimuli (Mather, & Sutherland, 2011).

According to the ABC model, whether arousal will enhance or impair perception of an item is dependent on that items´ priority. Arousal will boost the competition between stimuli, benefiting perception of high priority information and depress perception of low priority information. What is considered high priority information in any given situation

varies greatly, and is dependent on top-down cognitive factors such as expectation and motivation as well as sensory bottom-up influences, in addition to aspects such as emotional and social relevance as well as the unexpectedness of information (Mather, & Sutherland, 2011).

Attention

Emotional objects draw attention and are detected quicker than neutral objects, especially so if the emotion-inducing item is of special relevance for the perceiver. Individuals with an intense fear of spiders, for example, detect pictures portraying spiders among distractor targets not only faster than emotionally neutral pictures, but quicker than other emotion-inducing pictures (such as a picture of a snake)(Öhman, Flykt, & Esteves, 2001).

Studies measuring event-related potentials (ERP) in individuals presented with emotional and neutral stimuli demonstrated that even in the earliest stages of processing, ERPs are faster to emotional content than neutral stimuli (Kissler, Herbert, Peyk, & Junghofer, 2007). In addition, emotional material is also more likely to register in conscious awareness. The *attentional blink* is a phenomenon that manifests when people are shown a series of images in rapid sequence. Attention to a second target is diminished when followed in short proximity to a first target (Shapiro, Raymond, & Arnell, 1997). In a study examining the impact of motivationally relevant stimuli in relation to the attentional blink (de Oca, Villa, Cervantes, & Welbourne, 2012) found that emotionally arousing pictures resisted the attentional blink-effect. Results like these support the idea that motivationally relevant stimuli capture attention more than emotionally neutral stimuli, and that emotionally arousing information in relation to neutral stimuli seems to have the advantage of more efficient and quicker early processing.

Schmidt and Saari (2007) performed a study investigating the cognitive factors of attention and distinctiveness in relation to emotional memory. The analysis revealed an increase in attention to emotional words, both taboo, and non-taboo when compared to neutral words. Also, enhanced memory was observed for emotional words. However, when the three types of words were presented in separate lists, the pattern changed. The memory enhancement of emotional non-taboo words disappeared while the memory advantage of emotional taboo words remained. This is an interesting finding indicating that the distinctiveness of emotional content in relation to neutral content may account for some of the memory advantages of emotional information over neutral. However, though attention was heightened for all emotional words, only increased attention to taboo words was associated with actual enhancement of memory, possibly because the taboo words were more arousing (Schmidt, & Saari, 2007).

Bottom-up

Unique items or stimuli tend to stand out when they appear among homogeneous distractors (Orsten-Hooge, Portillo, & Pomerantz, 2015), and items are easily perceived when they are distinct from their surroundings, whether that contrast is derived from a difference in motion, orientation, color, or luminance (Nothdurft, 2000).
ABC posits that arousal acts as an agent, amplifying this effect (Nothdurft, 2000), enhancing contrast and inhibiting the perception of the surrounding context, in relation to a non-arousing situation (Mather, & Sutherland, 2011).

Top-down

Top-down components such as prior knowledge, expectations, and in particular its relevance to motivational goals also determine which stimuli gain priority over other irrelevant stimuli (Mather, & Sutherland, 2011). A study that employed functional MRI

(fMRI) and event-related potential recordings (ERPs) to study the ability to selectively attend to relevant stimuli and to ignore irrelevant stimuli found results consistent with this idea. The researchers directed the participants to watch pictures of scenes and faces. In one condition the participants were instructed to remember the scenes and ignore the faces, and in another, they were told to ignore the scenes and remember the faces. The results showed that directing the participants to remember scenes while seeing both types of picture led to above-baseline activity in the parahippocampal place area. Conversely, remembering faces during the showing of pictures led to below-baseline activity in the parahippocampal place area (Gazzaley, Cooney, McEvoy, Knight, & D'Esposito, 2005). This demonstrates that top-down influences can both suppress and enhance neural representation of perceived stimuli.

The ABC model predicts that goal-relevant stimuli will benefit from arousal, gaining increased priority while at the same time decreasing priority for goal-irrelevant stimuli (Mather, & Sutherland, 2011).

The Frontoparietal Attention System

It seems that emotional arousal increases the effect of top-down attentional goals (Mather, & Sutherland, 2011). The prevailing view on selective attention is that two separate but interconnected cortical systems direct attentional operations and are paramount for implementing goal-directed selection in attention and memory retrieval; the dorsal frontoparietal attention system and the ventral frontoparietal attention system (Gazzaniga, Ivry, & Mangun, 2014). The dorsal frontoparietal attention system is mainly involved in mediating the top-down guided voluntary allocation of attention to locations or features. It includes the frontal eye fields (FEF) located in the dorsal lateral posterior prefrontal cortex, as well as the intraparietal sulcus (IPS), the superior parietal lobule (SPL), and precuneus (PC) in the posterior parietal lobe (Vossel, Geng, & Fink, 2014). The ventral frontoparietal attention system is mostly lateralized to the right hemisphere and encompasses the ventral frontal

cortex (VFC), including the inferior and frontal gyrus, and the temporoparietal junction. The ventral system is believed to be mostly involved in stimulus-driven attentional control, such as detection of salient, or unexpected targets, as well as when sudden shifts of attention are required (Vossel et al., 2014).

Lim, Padmala, and Pessoa (2009) conducted a fMRI study investigating how affective significance shapes visual perception and the involvement of the amygdala. They had participants performing an attentional-blink task, trying to detect two target objects in a rapid stream of distractors. Some of the target objects had in a previous learning phase been conditioned to be either arousing or neutral. In line with results from other studies (e.g., de Oca et al., 2012) they found that participants were more likely to detect the second target if it was arousing compared to when it was not, even though the targets in this study did not differ perceptually. The analysis also revealed stronger amygdala and visual cortical responses for correctly identified arousing targets than for neutral targets. Additionally, the impact of the amygdala on the visual cortices was indicated to be mediated by activity in frontoparietal regions (inferior parietal lobule (IPL), middle frontal gyrus (MFG), and superior frontal gyrus (SFG)). As these regions are considered to be part of the frontoparietal attention network (Vossel et al., 2014), this lends support for the idea that the amygdala drives the arousal effect by modulating activity in the frontoparietal attention network to direct attention towards high priority stimuli.

Arousal in the study by Lim et al. (2009) appears to have enhanced the impact of the top-down attentional goals, allowing the participants to detect the targets. However, when the goal-relevant stimuli is not emotional, but emotional stimuli are present, arousal may hinder and distract people from their goal, as emotional stimuli in themselves attract attention (Nummenmaa, Hyönä, & Calvo, 2006). In such a situation, it would be reasonable to expect the amygdala to still modulate frontoparietal attention network activity, but in contrast

to a situation in which the emotional stimuli and the goal-relevant stimuli coincide, the amygdala should decrease the force of goal-directed selection by prioritizing the emotionally relevant distractor.

Mitchell et al., (2008) performed a fMRI study investigating the neural activity associated with the interfering effects of emotional distractors. In one condition they had participants press buttons in response to specific target stimuli that was followed and preceded by either emotional or neutral images, and in another, the participants were simply presented with the different distractors. Increased activation was observed in the amygdala in the presence of positive and negative distractors, relative to neutral distractors. In accordance with current models of attention (Vossel et al., 2014), lateral superior frontal gyrus (SFG) and parietal cortices showed an activity increase when participants experienced emotional distractors in a distractor-only condition, presumably in reaction to the detection of a salient stimulus. Conversely, in the response-with-distractor conditions, activity in the frontoparietal network decreased while activity in amygdala increased (Mitchell et al., 2008).

These findings in addition to those of Lim et al. indicate that the amygdala impacts the way in which attention is guided by top-down goals, possibly influencing activity in the frontoparietal attention network. The effect of this modulation can both enhance and debilitate top-down goal-directed selection, depending on whether or not the source of arousal coincide with current task goals (Mather, & Sutherland, 2011).

Emotional relevance

Emotional relevance is an important factor that may determine priority. There are many studies that show results in line with the idea that emotional stimuli stand out more than neutral stimuli. For example, when presenting an arousing picture and a neutral picture together, the gaze of participants is not only more likely to find the emotional picture first, but also fixate longer on the emotional stimuli than the neutral picture (Knight et al.,

2007; Rosler et al., 2005). Even when specifically instructed not to look at the emotional pictures, the same pattern remains (Nummenmaa et al., 2006). Furthermore, brain activity suggesting prioritized processing of emotional stimuli has been found in multiple sensory systems. For instance, Zald and Pardo (2002), used measures of regional cerebral blood flow (rCBF) to investigate the brain activity of participants while being exposed to unpleasant sounds. In addition to the expected increase of rCBF in the lateral amygdala, increased activity was also found in the auditory cortex, relative to a white noise control condition. In another study, the same type of enhanced activity was observed when participants viewed actual emotional faces embedded in noise as when they watched a neutral face but thought they were watching an emotional face (Lee et al., 2010).

Emotional stimuli thus seem to gain priority both from bottom-up processes stemming from perceptual contrast as well as top-down cognitive factors guiding perception. ABC theory predicts that arousal, whether induced by the emotional stimulus itself or generating from another source, should further amplify this competitive advantage of emotional over neutral stimuli (Mather, & Sutherland, 2011).

Perception

Mather and Sutherland (2011) tested the notion that arousal amplifies perceptual salience of high priority stimuli. They played an arousing or non-arousing sound, after which the participants were presented with an array of letters, out of which five were printed in low-contrast grey and three were printed in high contrast grey. The participants then were asked to report which letters they perceived. As could be expected, since the high-contrast letters were more distinct (Nothdurft, 2000), the participants were more likely to report high-contrast letters than low-contrast letters. However, this trend was enhanced when the participants were first exposed to the arousing sound (Mather, & Sutherland, 2011). Thus, it seems that arousal

amplified the competitive benefit of perceptual salient stimuli over less salient stimuli in gaining mental representation.

An example of arousal amplifying an already high priority stimulus comes from Stefanucci and Storbeck (2009), who in a series of experiments demonstrated that arousal influenced height perception. Participants were instructed to view arousing or non-arousing pictures, after which they were asked to verbally estimate the height of the balcony they stood on. Results showed that viewing arousal inducing pictures before making the judgment made participants overestimate the height of the balcony more than those who viewed non-arousing images.

When one image is presented to one eye separately and another image is presented to the other, a phenomena known as binocular rivalry occurs. Instead of perceiving both images as superimposed, perception alternates between the two images (Freeman, & Nguyen, 2001). It has been demonstrated that the emotionality of the images affects the selectivity of perception. Emotional pictures dominate awareness to a higher degree than neutral pictures (Alpers, & Pauli, 2006), and whether the stimuli are pleasant or unpleasant does not seem to matter (Bhavin, & Thuan, 2008). One study used functional magnetic resonance imaging (fMRI) to investigate whether arousal enhances processing of salient information while decreasing brain activation associated with the processing of less salient stimuli. Lee, Sakaki, Cheng, Velasco, and Mather, (2014) showed two images simultaneously; one salient stimulus consisting of a face highlighted further with a yellow frame, and an image of a scene as the non-salient stimulus. The viewing was preceded by either an unconditioned tone or a tone that had previously been conditioned to predict shock, and thus induce arousal. An arousal-by-saliency interaction was found, indicating that arousal enhanced activation in the region processing the salient material (fusiform face area) whilst

activation in the region processing the non-salient material (parahippocampal place area) was suppressed.

Memory narrowing

The notion that arousal narrows attention is not a new one. Easterbrook (1959) put forward the idea that stress and arousal curtail the number of cues used in a situation, limiting attention to peripheral cues in favor of central and more directly relevant cues. Likewise, later research suggested that emotional arousal enhances memory for central details of a stressful experience at the expense of memory for peripheral details. This effect, called memory narrowing, has been well established (Levine, & Edelstein, 2009; Rush, Quas, & Yim, 2010). A well-known example of this is the so-called weapon focus effect (Loftus, Loftus, & Messo, 1987) where a witness to a crime may have a hard time remembering peripheral details such as the clothes of a perpetrator but vividly recalls, and sometimes exaggerates, the perception of a weapon (Fawcett, Russel, Peace, & Christie, 2013).

Multiple studies have shown that when an arousing object is presented on a neutral background, people tend to remember the central arousing stimuli better than the emotionally neutral background (e.g., Kensinger, Garoff-Eaton, & Schacter, 2007). Waring and Kensinger (2009), demonstrated this when they had participants view images with neutral or emotional valence placed on neutral background scenes. First, as would be expected, they established that images with emotional significance were better remembered than central images with emotionally neutral content. Additionally, in conditions with a central arousing stimulus present, the neutral background was more poorly remembered than if the central picture was emotionally neutral. This exemplifies the trade-off effect of the emotional memory advantage.

In the view of the ABC theory, findings presumably revealing a memory narrowing effect of arousal instead actually displays instances in which arousal enhances representation of information that just happens to be centrally situated. As previously stated, ABC theory predicts that arousal will benefit information with the highest priority, at the cost of information with lower priority (Mather, & Sutherland, 2011). Thus, arousal may bias competition of emotionally arousing items because of their perceptually salient nature. If such an item is presented in a central location, this may be interpreted as memory narrowing. If, however, the background information for some reason gained priority, then mental representation for it instead would be strengthened.

One study exemplifies how top-down goal-directed selection may affect the arousal-induced memory trade-offs. When participants passively viewed scenes depicting a central object (either neutral or negatively arousing) on a neutral background, robust subsequent emotion-induced memory trade-offs were found for emotional objects (Kensinger, Gutchess, & Schacter, 2007). Participants showed an arousal effect favoring memory for details as well as the gist of central emotional objects at the expense of memory for background information. More interestingly though, when participants received specific instructions to encode the entire scenes, this trade-off effect dissipated.

Gist versus Details

In addition to findings suggesting a memory narrowing effect of arousal there are indications in the literature that arousal may affect different aspects of the to-be-remembered stimuli differentially, possibly enhancing processing of central aspects of a stimulus (i.e, *gist*), at the expense of specific sensory information (i.e, *details*) (e.g., Kensinger, Gutchess, et al., 2007). Stress-induced arousal has been demonstrated to disrupt the ability to distinguish actually perceived words in a study list from semantically related

lure words (Payne, Nadel, Allen, Thomas, & Jacobs, 2002), indicating biased processing of gist information. Liu, Graham, and Zorawski (2008) showed enhanced later recall of images with emotional content when participants experienced post-encoding arousal compared to controls. In addition, participants exposed to post-encoding arousal exhibited enhanced gist memory for pictures, but no enhancement of memory for details was found. Another study assessed subsequent memory for gist information and detail in healthy individuals and participants with unilateral amygdala damage, in addition to one participant with bilateral amygdala damage. In accordance with other research cited above, it was found that both controls and patients with unilateral amygdala damage exhibited enhanced memory for the gist information related to the emotional pictures as compared to gist information related to neutral pictures. More interestingly, however, was that the patient with bilateral amygdala damage showed an opposite pattern, displaying better memory for the gist of the neutral pictures than for the emotional pictures (Adolphs, Denburg, & Tranel, 2001). In a later follow-up study somewhat contradicting findings were demonstrated in which this reverse pattern was also found in patients with unilateral medial temporal lobe damage, whereas controls showed enhanced gist memory compared to details (Adolphs, Tranel, & Buchanan, 2005). Such findings highlight the amygdala as an important modulator of increased processing of gist information.

However, findings supporting emotion-induced memory enhancement of gist at the expense of details are not conclusive. For example, Libkuman, Nichols-Whitehead, Griffith, and Thomas, (1999), found no enhancement of gist memory generated by emotional arousal in relation to controls. In addition, contrary to findings mentioned previously, no memory trade-off for peripheral details as a result of emotional arousal could be established. Results instead indicated enhanced memory for both central and peripheral detail. Others found emotion-induced memory enhancement for central details, but no increase in memory

for gist or peripheral details of a narrative (Otani, Libkuman, Widner, & Graves, 2007). Likewise, individuals typically seem to remember more specific details of emotional items than nonemotional items (Kensinger, Garoff-Eaton, et al., 2007). One study found that emotionally negative central items presented on a neutral background, produced enhanced gist memory and memory for specific details of the negative items, but decrements in memory for details of the background. However, when instructed to attend to all the visual details of the scenes, the memory trade-off for central versus peripheral elements of scenes were eliminated (Kensinger, Garoff-Eaton, et al., 2007).

Studies such as those presented above highlight the inconsistencies in findings relating to gist-detail, and central-periphery trade-offs induced by emotional arousal. Neither notion seems to hold up across all contexts and delivers limited predictability as to what will be enhanced by arousal. The ABC view explains findings such as those described as not necessarily contradicting. Instead, what is highlighted as paramount is the relative relevance of competing stimuli (Mather, & Sutherland, 2011). In many instances, the most prominent aspect of an event may very well be the overarching theme, resulting in an increased likelihood for gist information to win the competition for mental representation at the expense of detail information. In other situations, it might instead be central components that are most salient (e.g., Otani et al., 2007), and arousal then would be expected to increase the dominance of central details over gist or peripheral information. It seems that whether or not arousal will enhance memory for gist or detail, or have a narrowing effect depends on what is most conspicuous and has priority during encoding, as seen in (Kensinger, Garoff-Eaton, et al., 2007).

Within-object Memory Binding

Findings also indicate enhanced memory for intrinsic features such as location and color of emotionally arousing items as compared to non-arousing items. However, this does not seem to be the case for the binding of associations between the emotional item and other co-presented items (Madan, Caplan, Christine, Lau, & Fujiwara, 2012; Madan, Fujiwara, Caplan, & Sommer, 2017; Mather, & Sutherland, 2009; Nashiro, & Mather, 2011). One study found enhancement of memory for peripheral information that occurred in the same context as emotion-inducing information (taboo words) (Guillet, & Arndt, 2009). This result seems to be at odds with the memory-narrowing account. However, viewed from the ABC perspective, this does not run counter to other findings. In Guillet and Arndt´s study, the participants were specifically instructed to quietly read the whole sentence including the taboo word in preparation for later questioning, or try to remember the word-pair that contained the emotion-inducing word, thus actively paying attention to the associations at encoding. According to ABC theory, this would constitute a task-goal that in a top down fashion should prioritize item-item associations (Mather, & Sutherland, 2011).

ABC theory predicts arousal-enhanced processing of high priority information and arousal-impairment of low priority information, independent of whether the heightened priority is due to top-down attentional goals or bottom-up perceptual salience. Thus, arousal may enhance associative memory for intrinsic features of an item, as well as between items, if the association is prioritized. Conversely, in a situation with an emotional item and neutral items presented together, arousal should typically impair associative memory between items as a consequence of the salient nature of the emotional item.

Retrograde Amnesia or Retrograde Enhancement?

The arousal associated with emotional stimuli does not only affect memory for the arousing item itself but may also affect memory for other items in proximity to the emotional stimuli. When an emotional item such as a picture or a word is presented in a list among other items, but are distinct from them, memory for items that precede or follow the emotional stimuli will typically be impaired (e.g., Bornstein, Liebel, & Scarberry, 1998; Hurlemann et al., 2005; Strange, Hurlemann, & Dolan, 2003). However, one study produced results showing an opposite arousal-induced retrograde memory enhancement effect. Anderson, Wais, and Gabrieli (2006) found that when a picture of neutral content (either a face or a house) was followed by an emotionally arousing picture, memory for the neutral information was enhanced at testing one week later, as compared to a situation in which the neutral target was followed by a picture with neutral content. Additionally, this effect did only manifest if the arousing stimulus succeeded the neutral target within 4-9 seconds after its introduction, and was not evident when the neutral stimulus instead was followed by highly distinctive items of low arousal value. This study highlights two factors to crucially influence retrograde memory enhancement; the level of subjective arousal experienced, and a restricted temporal window in which arousal affects processing of preceding items.

Knight and Mather (2009) managed to demonstrate both retrograde enhancement and retrograde impairment in the same paradigm, further elucidating the conflicting effects of emotional stimuli on memory for preceding items. Their findings indicated key factors that determine the impact of emotional stimuli on memory for neutral items. Arousal-induced memory enhancement was most likely to occur for neutral items that were prioritized in attention during encoding and were presented before the emotionally arousing item. Additionally, the retrograde enhancement effect of arousal only appeared when testing for retention after a delay of one week rather than immediately after encoding. Retrograde impairment effects of arousal were most likely when testing for memory

immediately after encoding, and when a larger set of neutral stimuli had been presented before the emotional item.

ABC theory accounts for these seemingly contradictory findings by delineating what stimuli gain initial priority. In studies such as in Hurlemann et al., (2005), perceptually similar neutral items compete for representation with a perceptually salient, and in addition, arousing stimulus. Arousal in such a scenario likely suppresses processing of the neutral stimuli in favor of the high-priority emotional stimuli. On the other hand, in the study by Anderson et al. (2006), the participants were asked to indicate whether or not they would remember the neutral images, which likely put top-down attentional focus on these items, resulting in increased priority. Furthermore, this study introduced only one image as the neutral target before showing the modulator picture, thus decreasing competition between preceding stimuli. The findings from Knight and Mather (2009), further support the ABC notion that stimuli with the highest priority before the onset of arousal will exhibit a strengthened representation in long-term memory, whereas a suppression of information with lower priority before the onset of arousal will occur (Mather, & Sutherland, 2011).

Glutamate Amplifies Nor-adrenergic Effects

The ABC model neatly accounts for the arousal-induced effects on memory by suggesting that arousal biases perception and attention towards information our intricate brain has deemed as high-priority, determined by factors such as saliency or motivational relevance. This biased contest for mental representation then continues with arousal acting to favor long-term consolidation of high-priority information, leading to subsequent enhanced memory for items and events that initially gained precedence. What the ABC model fails to clarify, however, is how this priority status is established and amplified as a consequence of arousal. One possible explanation comes from a newly formulated model that emphasizes glutamate

interactions with norepinephrine as critical for inducing the activation difference between high- and low-priority neural representations.

According to the glutamate amplifies nor-adrenergic effects (GANE) model, glutamate, which is the most prevalent excitatory neurotransmitter in the brain, is paramount for signaling priority. Elevated glutamate levels associated with highly active neural representations are further enhanced by the surge in NE release induced by arousal. High levels of NE engage adrenoreceptors that act to further increase NE and glutamate release at local sites of prioritized neural representations while at the same time suppressing most other neural activity. This high concentration of NE also directs energy resources to be more readily available at the site of the highly active neural representation. Thus, during arousal, widespread NE suppression of neurons transmitting lower-priority information, are contrasted with local NE hotspots where glutamate signaling is amplified. In this way, NE promotes selectivity for any prioritized stimuli in memory and perception, regardless of how this priority came about, and irrespective of whether the stimulus is in itself emotional or not. (Mather, Clewett, Sakaki, & Harley, 2016).

The locus coeruleus (LC), situated in the brainstem, contains norepinephrine (NE) -synthesizing neurons (Keren, Lozar, Harris, Morgan, & Eckert, 2009). During arousal, whether induced by a provoking image, a loud noise, reward or punishment, the LC releases norepinephrine (NE). The LC is involved in regulating arousal levels and is the main source of cortical NE (Berridge, Schmeichel, & Espana, 2012). During non-arousing situations, tonic activity of the LC helps regulate the degree of wakefulness (Carter et al., 2010), and the LC exhibit bursts of phasic activity in response to emotionally salient, threatening, novel or otherwise behaviorally relevant stimuli (Sara & Bouret, 2012) and to top-down signaling (Aston-Jones & Cohen, 2005). The LC sends diffuse projections throughout the central nervous system including every major region of the cortex, and to subcortical regions

underlying emotional, memory and attention processing such as the amygdala, frontoparietal cortex, and hippocampus. These widespread projections enable NE to influence processing both locally and globally in the brain (Berridge & Waterhouse, 2003; Mather et al., 2016).

In these various sites, NE binds to different types of adrenoreceptors (i.e., α1, α2, and β receptors), leading to diverse effects. β-adrenoreceptors are engaged at relatively high concentrations of NE, whereas α1-adrenoreceptors require more moderate levels. α2-adrenoreceptors require the lowest levels of NE to be engaged (Ramos & Arnsten, 2007). Whereas activation of β- adrenoreceptors tend to increase synaptic plasticity and, like α1-adrenoreceptor activation, typically inflate cell excitability, α2- adrenoreceptor activation decreases local cell excitability and act as autoreceptors, restricting NE release (Marzo, Bai, & Otani, 2009; Wang & McCormick, 1993). Thus, the effect of arousal-induced NE release on various areas of the brain is in part determined by the localization and relative density of the different receptor subtypes.

The engagement of these adrenoreceptors has different effects depending on the local level of NE. β- adrenoreceptors are activated at high levels of NE and act to further amplify NE release (Murugaiah & O'Donnell, 1995). Conversely, α2- adrenoreceptors inhibit further NE release when engaged at low levels of NE (Langer, 2008). Furthermore, when neurons are depolarized, α2- adrenoreceptors may lose affinity for NE. This effect is then reversed when NE reaches saturating levels (Rinne, Birk, & Bünemann, 2013). In this fashion the inhibitory influence of α2- adrenoreceptors is eliminated at highly active regions, while the eventual recovery of affinity regulates the NE-glutamate feedback loop, preventing runaway excitation. The combination of glutamate-evoked NE release and the adverse effect of varying NE concentrations on different autoreceptors, enables the LC, depending on the level of local excitation, to modulate signal gain.

Glutamate

Glutamate typically has an excitatory effect on postsynaptic neurons and is the most prevalent excitatory neurotransmitter in the hippocampus and in the brain as a whole (Gazzaniga et al., 2014; Okubo et al., 2010). Glutamate binds to the receptors NMDA (N-methyl-D-aspartate) and AMPA (α-amino-3- hydroxy-5-methyl-4-isoxazolepropionic acid) which facilitates fast excitatory synaptic transmission (Traynelis et al., 2010) , mediates long-term potentiation (Gazzaniga et al., 2014) and thus plays an important role in learning and memory by increasing synaptic connections.

Local hotspots with elevated NE concentrations activate β-adrenoreceptors at glutamate terminals signaling prioritized representations. The engagement of β-adrenoreceptors induces an even greater release of glutamate, further boosting the excitatory high priority neural transmission (Kobayashi et al., 2009). Conversely, the engagement of α2-adrenoreceptors inhibits glutamate release (Egli et al., 2005). This provides mechanisms for enhancing the glutamate signaling of high priority representations while at the same time inhibiting lower priority representations. In addition to direct point-to-point transmission across a synapse, Okubo et al. (2010) demonstrated that during synaptic activity some glutamate escapes the synaptic cleft and can activate extrasynaptic receptors in the vicinity as well as bind to receptors in neighboring synapses, an effect referred to as “glutamate spillover”. According to the GANE model, this spillover effect enables glutamate to attract and enhance local NE release, leading to even greater glutamate signaling in the vicinity of synapses transmitting prioritized neural representations in positive feedback loops. Wherever NE is released but fails to reach levels high enough to engage β-adrenoreceptors, α2-adrenoreceptors that are engaged at much lower NE levels act as autoreceptors and suppress

neural activity. This leads to local NE hotspots against a quieter backdrop (Mather et al., 2016).

NE is also involved in regulating and coordinating the delivery of essential energy supplies to relevant areas of the brain (Toussay, Basu, Lacoste, & Hamel, 2013). Glucose and oxygen are delivered via the bloodstream and are paramount for normal brain functioning and cellular respiration (Gazzaniga et al., 2014). It has been demonstrated in mice that when NE levels are increased, using an α2-adrenoreceptor antagonist, blood vessel diameter in the brain decreases overall. However, this vasoconstriction redistributes blood flow to task-relevant active regions (Bekar, Wei, & Nedergaard, 2012). Furthermore, another storage for energy is in glycogen that is found throughout the cell body of astrocytes. When glycogen is broken down, it can be converted into glucose and used as energy by muscles and the brain. This process is also affected by NE. Engaged β-adrenoreceptors trigger the degradation of glycogen, which can provide energy to local areas during critical periods of high demand. NE increases glutamate uptake and enhances both the production and breakdown of glycogen (O'Donnell, Zeppenfeld, McConnell, Pena, & Nedergaard, 2012).

Taking these findings together it seems that the locus coeruleus–norepinephrine (LC–NE) system provides a way for arousal to amplify the difference in activation between low-priority and high-priority neural representations via local synaptic self-regulating feedback loops. The neural transmission in highly active sites of representation is further amplified by positive feedback loops between NE and glutamate release, resulting from the contrasting effect of NE on different adrenoreceptor subtypes. Further biasing processing towards that of prioritized information, the increase in NE and glutamate in these highly active regions also recruits energy resources from nearby astrocytes, while NE directs blood flow towards these areas and away from areas exhibiting lower activity.

Consolidation

As has been discussed previously, arousal augments the competition between stimuli, favoring processing of high priority information during initial perception and encoding. According to ABC theory, this effect continues after encoding, strengthening memory consolidation for high priority items and information while decreasing memory consolidation for low priority stimuli. In addition, the ABC-model further predicts that arousal will magnify competition between preexisting, currently active mental representations, thus potentially modulating consolidation of items experienced prior to the onset of arousal (Mather, & Sutherland, 2011).

The process that stabilizes an initially labile memory and creates a stronger mental representation over time is called consolidation. The model of consolidation is based on the assumption that newly encoded memories are unstable and susceptible to interference but stabilize and becomes resistant to interference as time passes (Sandrini, Cohen, & Censor, 2015). Diverse findings in the literature suggest that consolidation processes are typically enhanced by post-encoding stress (e.g., Smeets, Otgaar, Candel, & Wolf, 2008) or glucocorticoid administration (e.g., Roozendaal, Okuda, Van der Zee, & McGaugh, 2006). While some results seem to suggest that emotional arousal enhances consolidation of emotional information, but not neutral information (e.g., Segal, & Cahill, 2009; Smeets et al., 2008), others has found evidence for arousal-induced consolidation enhancement of neutral information as well (e.g., Knight, & Mather, 2009; Nielson, & Powless, 2007). What differs between the studies mentioned above is that those that used a paradigm in which emotional and neutral items were presented intermixed to participants in a study list, found enhancement in later recall performance for emotional items only (Segal, & Cahill, 2009). If, however, the to-be-remembered information was emotionally neutral, post-encoding arousal led to subsequent memory enhancement for the neutral information (Nielson, & Powless, 2007).

ABC theory explains these mixed findings as a consequence of differences in stimulus priority during initial encoding. As previously discussed, when an item or stimulus is in itself emotionally arousing it will gain priority over non-emotional information due to the conspicuous nature of the emotional stimulus. Thus, post-encoding arousal should result in improved consolidation of emotional items in a list containing both neutral and emotional features. However, as an effect of top-down goal relevance, in situations where the neutral information is the focus of attention, post-encoding arousal should benefit consolidation of the to-be-remembered neutral information (Mather, & Sutherland, 2011).

Epinephrine

One of the very first reports indicating that epinephrine may be involved in memory modulation came from Gold and Van Buskirk (1975). They injected epinephrine in rats after training on an inhibitory avoidance task and found subsequently enhanced retention for rats that had received injections immediately after training, compared to controls that received saline injections. As epinephrine does not easily cross the blood-brain barrier (McGaugh, Cahill, & Roozendaal, 1996), it may be that this adrenomedullary hormone acts on memory processes by activating β-adrenoceptors on vagal afferents that connect to the nucleus of the solitary tract (NTS), which in turn projects to forebrain regions via the locus coeruleus (LC). The LC may thus act as an interface between peripheral adrenergic activation and other processes that are involved in regulating memory consolidation (Roozendaal, & McGaugh, 2011).

When solatol, a β-adrenoceptor antagonist, is administered, it blocks the enhancing effect of peripherally injected epinephrine on memory (Introini-Collison, Saghafi, Novack, & McGaugh, 1992). Since solatol does not readily enter the brain (Roozendaal, & McGaugh, 2011), this strengthens the notion that epinephrine has an indirect effect on

memory modulation. One study investigated the modulating effect of post-learning systemic induction of epinephrine (EPI) on short-term and long-term memory in a low-arousing training experience (Jurado-Berbel, Costa-Miserachs, Torras-Garcia, Coll-Andreu, & Portell-Cortes, 2010). While no memory improvements were found when tested 3 hours after the learning-phase, significant improvements were found when testing for long-term retention (24 h. and 48 h. after learning-phase). Roozendaal et al. (2008) administered norepinephrine (NE), the β-adrenoceptor antagonist propranolol or saline directly into the basolateral amygdala (BLA) after object recognition training. Compared to the saline condition, they found dose-dependent enhancement of object recognition in the norepinephrine condition, while propranolol administered after training produced dose-dependent memory impairments.

These findings suggest that post-training administration of epinephrine and norepinephrine can facilitate long-term memory for neutral information experienced before hormone induction. In addition, by infusing norepinephrine or propranolol directly into the BLA, Roozendaal et al. (2008), linked these effects to the amygdala, suggesting that noradrenergic activation of the BLA modulates long-term memory consolidation.

Glucocorticoids

The release of glucocorticoids as a result of emotionally arousing stimulation has been shown to play an important function in modulating memory consolidation and underlie both impairing and enhancing effects of arousal on memory processes (Sandi, & Pinelo-Nava, 2007). The injection of glucocorticoids has been demonstrated to produce dose-dependent as well as time-dependent enhancement of memory (Okuda, Roozendaal, & McGaugh, 2004). The effects of glucocorticoids on memory modulation seem to depend on the activation of GRs (Roozendaal, Portillo-Marquez, & McGaugh, 1996).

Adrenergic-Glucocorticoid Interactions

A number of studies have provided evidence indicating that memory consolidation and neural plasticity is influenced by interactions of catecholamines and glucocorticoids (e.g., Joëls et al., 2011).

Roozendaal, Carmi, and McGaugh (1996), demonstrated dose-dependent memory enhancement for inhibitory avoidance training in rats when injected with epinephrine post-training. However, administering metyrapone, a substance that inhibits the synthesis of corticosterone, before introducing epinephrine attenuated the memory-enhancing effect. One study produced results suggesting that emotional arousal may be essential for glucocorticoid effects on memory (Okuda et al., 2004). Rats that experienced novelty-induced arousal showed memory benefits of post-training corticosterone injections, while highly habituated rats did not exhibit enhanced retention as a result of corticosterone. Similarly, while Roozendaal et al. (2006) found evidence suggesting that glucocorticoid hormones enhance the consolidation of long-term memories for emotionally arousing experiences, their findings also indicated that simultaneous noradrenergic activation of the BLA was a necessary prerequisite for glucocorticoid-induced memory enhancement. Corticosterone was administered to rats immediately after object recognition training. 24 hours later object recognition memory was enhanced, but only for those rats that had not prior been habituated to the training context, and thus presumably experienced novelty-induced emotional arousal. This was corroborated by the fact that the corticosterone-induced memory enhancement was blocked by administration of the β-adrenoceptor antagonist propranolol. Conversely, in habituated rats, a corticosterone-induced memory enhancement and BLA activation could only be demonstrated with concurrent norepinephrine release, stimulated by administration of the α-adrenoceptor antagonist yohimbine.

These findings provide strong evidence that the sympathoadrenal and adrenocortical systems act interactively in influencing processes of memory storage and

indicate that adrenergic activation is crucial a component in enabling glucocorticoid augmentation of memory consolidation.

Noradrenergic Influences in the Basolateral Amygdala

Many findings suggest that the amygdala is involved in influencing memory consolidation. More specifically, it seems that the basolateral Amygdala (BLA) modulates memory, especially for events and stimuli of emotional significance, during post-learning periods of consolidation (Campolongo et al., 2009; Chavez et al., 2013). Furthermore, results from animal studies investigating the effect of posttraining intraamygdala drug treatments, indicate that such interventions particularly affects long-term consolidation (e.g., Barros, Pereira, Medina, & Izquierdo, 2002).

Numerous studies have presented evidence suggesting that noradrenergic activation within the amygdala mediates the effect of epinephrine on memory. Intra-BLA post-training infusion of norepinephrine enhances memory consolidation in rats (Huff, Wright-Hardesty, Higgins, Matus-Amat, & Rudy, 2005), while propranolol, a β-adrenoceptor antagonist, blocks the memory-enhancing effect of coadministered norepinephrine (Liang, Juler, & McGaugh, 1986). Roozendaal et al. (2008), tested rats in a low-arousing object recognition task and found dose-dependent memory enhancement of intra-BLA infusions of norepinephrine (NE) when administered post-training, whereas post-training administration of propranolol produced dose-dependent impairment of memory. Such findings suggest, besides indicating a mediating role of the BLA in epinephrine-induced memory effects, that even in the absence of arousal stemming from a sensory experience, noradrenergic activation of the BLA can modulate memory consolidation.

Roozendaal, and McGaugh (2011) reasoned that the available evidence highlighting adrenoceptor activation within the amygdala as a modulating factor for memory

consolidation implied two distinct predictions. First, that emotional arousal should induce the release of NE within the amygdala, and secondly, that hormones and drugs that augment memory consolidation should increase the release of NE. In line with this notion, it has been demonstrated that the type of footshock stimulation typically used in inhibitory avoidance training, markedly increases the release of NE in the amygdala in varying degrees depending on the intensity of the footshock (Quirarte, Galvez, Roozendaal, & McGaugh, 1998). Likewise, other findings demonstrated a high correlation between subsequent retention performance and increases in amygdala norepinephrine levels as a result of inhibitory avoidance training (McIntyre, Hatfield, & McGaugh, 2002). Drugs that impair consolidation processes also decrease levels of norepinephrine in the amygdala, while consolidation enhancing drugs potentiate increases in norepinephrine from footshock stimulation (Roozendaal, & McGaugh, 2011). For example, while administration of the opioid peptidergic antagonist naloxone immediately after footshock augments the release of NE, administration of the opioid peptidergic agonist β-endorphin instead blocks the footshock-induced increase in NE levels (Quirarte et al., 1998). Furthermore, while stimulation of the nucleus of the solitary tract (NTS) enhances consolidation and boost norepinephrine levels in the amygdala (Clayton, & Williams, 2000), inactivation of the NTS attenuates the increase in amygdala norepinephrine levels induced by systemic injection of epinephrine (EPI) (Williams, Men, Clayton, & Gold, 1998).

Amygdala Interactions with Other Brain Regions

Besides studies that have used inhibitory avoidance training to investigate the role of BLA in memory consolidation (eg., LaLumiere, Nguyen, & McGaugh, 2004; Parent, & McGaugh, 1994), others have found similar effects of post-training amygdala treatments using a variety of different training tasks, including object recognition (Roozendaal et al.,

2008), water-maze spatial training (Packard, & Teather, 1998), and fear conditioning (LaLumiere, Buen, & McGaugh, 2003). As such training tasks engage different brain systems (Roozendaal, & McGaugh, 2011), this indicates that the BLA is involved in modulating processing in different brain regions.

Findings from studies on rats provide evidence that the influence of the amygdala on memory consolidation processes is not selective to specific types of information. The amygdala projects both indirectly and directly to the hippocampus and to the caudate nucleus via the stria terminalis (Roozendaal, & McGaugh, 2011), and evidence suggests that these sites are involved in different features of memory functions. The prevailing hypothesis is that the hippocampus mediates cognitive memory while the caudate nucleus mediates stimulus-response memory formation (Packard, & Cahill, 2001). This notion is strengthened by findings that post-training infusion of amphetamine into the caudate nucleus enhanced performance in a cued water-maze task, while amphetamine infusion into the hippocampus selectively enhanced memory of a spatial training task. Inactivation of caudate nucleus or hippocampus before testing, using lidocaine, blocked retention of the cued task and spatial task respectively, whereas inactivation of the amygdala did not block of retention of either triaging task (Packard, & Teather, 1998). This indicates that although the amygdala is involved in modulating consolidation of both hippocampus-dependent and nucleus-dependent memory it does not seem to be a critical storage site for either type of memory. Evidence suggesting BLA-hippocampus interactions in memory consolidation is further strengthened by findings that post-training intrahippocampal infusion of a glucocorticoid receptor agonist (RU 28362), enhances retention of an inhibitory avoidance training task. Interestingly, neurochemically lesions of the BLA blocked this memory modulatory effect (Roozendaal, & McGaugh, 1997), indicating the BLA as a critical site involved in regulating the effect of glucocorticoids on memory processes in other brain areas.

The BLA projects to the nucleus accumbens (NA) via the stria terminalis (Roozendaal, & McGaugh, 2011), and evidence suggests the involvement of this pathway in influencing memory consolidation. Setlow, Roozendaal, and McGaugh (2000), used neurochemical lesions in combination with post-training injections of the synthetic glucocorticoid dexamethasone, to investigate the involvement of the NA in memory consolidation in rats. The data showed the expected results that in the control animals, post-training injections of dexamethasone significantly enhanced retention. However, in rats with bilateral lesions of the NA, this effect was blocked. In a subsequent experiment, it was further revealed that rats with unilateral lesions of the BLA and ipsilateral unilateral lesion of the NA exhibited the aforementioned dexamethasone-induced retention enhancement. On the other hand, in rats with unilateral lesions contralateral to the concurrent unilateral lesion of the BLA, this effect was blocked, thus further indicating that an intact BLA-stria terminalis-NA pathway is paramount for glucocorticoid-induced effects on memory consolidation.

Activity-regulated cytoskeletal protein (Arc) is an immediate-early gene whose expression has been implicated as a marker of neural activity relating to hippocampal synaptic plasticity and memory consolidation (Donzis, & Thompson, 2014). McIntyre et al. (2005), found that post-training intra-BLA infusions of the β-adrenoreceptor agonist clenbuterol, enhanced memory on an inhibitory avoidance task at testing 48 hours later. More interestingly, however, was the finding that the same dose of clenbuterol significantly increased Arc protein levels in the dorsal hippocampus. Moreover, infusions of lidocaine to inactivate the BLA led to significant decreases in Arc protein levels in the dorsal hippocampus. These results provide evidence suggesting that the BLA may be actively involved in modulating memory consolidation by regulating Arc expression within the hippocampus.

Items that evoke increased amygdala activation during encoding also produce an increased hippocampal response at retrieval, compared to neutral items (Strange, & Dolan, 2004). Furthermore, this effect is abolished when introducing the β-adrenoceptor antagonist propranolol at encoding, thus suggesting that β-adrenergic engagement during encoding modulates the amygdala-hippocampal interactions.

In addition to influencing memory consolidation processes in sites such as the hippocampus and nucleus accumbens, available evidence suggests that the BLA impacts cortical functioning engaged in memory consolidation. Roozendaal et al. (2009) found that post-training unilateral infusion of a GR agonist (RU 28362) into the left mPFC produced increased retention performance on an inhibitory avoidance training task, while this memory-enhancing effect was blocked by an ipsilateral lesion of the BLA. In a second experiment, the intra-mPFC infusion of RU 28362 post-training was associated with increased BLA activity, assessed by increases in levels of phosphorylated extracellular signal-regulated kinase Type 1 and 2 (pErk1/2). When this increase was blocked by the infusion of an agonist (PD98059) into the BLA, the previously observed memory enhancement was prevented. On the other hand, administering the GR agonist RU 28362 into the BLA post-training increased levels of pErk1/2 in the mPFC (Roozendaal et al., 2009). Likewise, others have found that when AMPA (α-amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid) receptors were inactivated, using the AMPA receptor antagonist CNQX, in either the mPFC or amygdala separately and both pre- and post-training, retention deficits on an inhibitory avoidance task followed. Pre-training inactivation of either structure separately, using lidocaine, also produced significant retention deficits (Liang, Hu, & Chang, 1996). These findings seem to suggest bidirectional interactions between the mPFC and the BLA as an underlying factor for glucocorticoid effects on memory consolidation.

The BLA projects to the nucleus basalis via the stria terminalis, which in turn instigates cholinergic activation of the cortex (Roozendaal, & McGaugh, 2011). Electrical stimulation of the BLA activates neocortical activity, and this effect is blocked by introducing scopolamine, a cholinergic-muscarinic receptor antagonist (Dringenberg, & Vanderwolf, 1996). Power, Thal, and McGaugh, (2002) showed the expected pattern of dose-dependent memory enhancement of post-training bilateral intra-BLA infusion of norepinephrine in an inhibitory avoidance task. However, rats with induced bilateral lesions of the nucleus basalis were not affected by the norepinephrine intervention. Cortical cholinergic activity stemming from intact projections from the BLA to the nucleus basalis thus seems to be vital for BLA influences on memory consolidation.

The BLA also projects directly to the entorhinal cortex (Roozendaal, & McGaugh, 2011). Infusion of the substance 8-Br-cAMP, an adenosine 3′,5′-cyclic monophosphate, into the entorhinal cortex post-training enhances retention 48 hours later. However, a chemically induced ipsilateral lesion of the BLA negates the enhancing effect of 8-Br-cAMP (Roesler, Roozendaal, & McGaugh, 2002). Cortical plasticity is also directly influenced by BLA activation. Stimuli that are behaviorally important gain increased representation in the cortex. For example, auditory training that pairs a tone with a conditioned stimulus (CS) shifts the tuning of neurons in the primary auditory cortex to the frequency of the CS. The level of representational gain is dependent on the inherent importance of the CS; the greater behavioral importance of the CS, the larger the area of representational gain (Weinberger, 2007). Pairing a tone with stimulation of the BLA (CS) has been shown to produce highly specific shifts in tuning of cells in the auditory receptive fields towards and to the CS (Chavez, McGaugh, & Weinberger, 2009), and this BLA-induced tuning of the tonotopic map is enduring, lasting for three weeks or more (Chavez et al., 2013).

These findings suggest that the BLA strengthens memory for events of emotional importance in part by altering specific cortical representations. The ability of the BLA activation to exert long-lasting, highly specific, learning-related modification of stimulus representations in the cortex may be a crucial part of the modulatory influence of the BLA in facilitating long-term memory formation.

Modulation of Human Memory Consolidation

There is ample evidence that amygdala activation is crucial for the enhancement of memory generally associated with emotional arousal in humans. The typical finding that emotionally arousing material are better remembered than neutral information (e.g. Buchanan, & Lovallo, 2001), is not seen in individuals with bilateral lesions of the amygdala (Adolphs, Cahill, Schul, & Babinsky, 1997).

In one early study investigating the relationship between amygdala activity during encoding and subsequent memory performance, evidence was found indicating that the amount of emotional arousal induced by emotional material is crucial in influencing memory, while valence (positive or negative) of the material did not seem to matter. Using positron emission tomography (PET), participant´s amygdala activity was assessed during viewings of emotionally arousing films. Three weeks later a surprise memory test was conducted in which recall of the films were assessed. The results showed a high correlation (+0.93) between amygdala activity during encoding and subsequent true recall (Cahill et al., 1996). Other studies using PET imaging have found similar results, demonstrating a high correlation between amygdala activity induced by emotional material and later subsequent recall (Hamann, Eli, Grafton, & Kilts, 1999; Hamann, Eli, Hoffman, & Kilts, 2002). Additionally, these studies found correlations between amygdala activity and subsequent memory for material of both positive and negative valence, further indicating the induced arousal to be

more important than valence in influencing retention performance. These results from PET studies have been corroborated by a fMRI study using an event-related design in a subsequent memory paradigm. Like the studies mentioned above, Canli, Zhao, Brewer, Gabrieli, and Cahill (2000) could establish a high correlation between amygdala activity during encoding and memory three weeks later for the emotional scenes viewed during scanning. Additionally, the results demonstrated that memory for scenes that the participants had rated as being the most emotion-inducing showed the most robust relationship with amygdala activity during encoding, highlighting the level of emotional arousal as an operative factor. Whether assessed over a prolonged period of several minutes, using PET imaging (e.g., Hamann et al., 2002), or on a stimulus-by stimulus basis, using fMRI (e.g., Canli et al., 2001), amygdala activity induced by emotional material predicts enhanced long-term memory for the emotional stimuli.

In accordance with animal studies (e.g. Huff et al., 2005; McIntyre et al., 2005), β-adrenergic activation of the amygdala also seems to be critical for the modulation of memory induced by the temporally brief emotional arousal used in event-related designs. Administration of the β-adrenoceptor antagonist propranolol at encoding blocks both the increase in amygdala activity induced by emotional material and the enhancement of subsequent recall performance otherwise seen of emotional material (Strange, & Dolan, 2004). Consistent with the results from animal research, studies using PET (Hamann et al., 1999) or fMRI (Ritchey et al., 2008) have shown that activation of the amygdala and hippocampal regions are correlated during encoding of emotional material and that this increase in connectivity correlates with subsequent recall, thus providing further evidence that amygdala activity modulates activity in other regions of the brain involved in memory processing.

Administration of cortisol pre-encoding enhances subject´s subsequent recall of words or pictures previously learned (Abercrombie, Kalin, Thurow, Rosenkranz, & Davidson, 2003; Van Stegeren, Roozendaal, Kindt, Wolf, & Joëls, 2010). Similar effects have also been obtained by administration of amphetamine before or immediately after encoding of a word-list (Soetens, Casaer, D'Hooge, & Hueting, 1995). Furthermore, submitting participants to cold-pressor stress, which instigates the release of adrenal stress hormones, after studying a word list generates enhanced performance when testing for retention twenty-four hours later (Smeets et al., 2008). Likewise, in a study using yohimbine, an α_2-adrenoceptor antagonist, to manipulate levels of circulating norepinephrine after viewing scenes depicting an emotional story, Southwick et al. (2002) found norepinephrine-related improvements in memory at testing one week later. Yohimbine had diverse effects on the subjects, and in some cases was no more effective than placebo in activating the norepinephrine system. Subsequently, the groups as a whole (yohimbine v.s. placebo) did not differ significantly in later memory performance. However, an analysis of plasma concentration of 3-methoxy-4-hydroxyphenylglycol (MHPG), a marker of central and peripheral norepinephrine activation, revealed a significant relationship between levels of norepinephrine-release and subsequent memory in all groups combined. Another study found a robust memory-enhancing effect of orally administered yohimbine, as well as a significant impairment of memory induced by orally administered metoprolol (O'Carroll, Drysdale, Cahill, Shajahan, & Ebmeier, 1999). These findings suggest that post-learning adrenergic modulation underlies the typical finding of enhanced memory for emotionally arousing material and events in humans.

In accordance with findings from animal studies (e.g., Okuda et al., 2004; Roozendaal et al., 2006) there are indications in the literature that stress positively affects subsequent memory in humans, especially for emotional material, only if a robust increase in both cortisol levels and emotional arousal is exhibited (Abercrombie, Speck, & Monticelli,

2006; Schwabe, Bohringer, Chatterjee, & Schachinger, 2008). This is further corroborated by findings that propranolol blocks the memory-enhancing effect of emotionally arousing material compared to emotionally neutral material (Van Stegeren, 2008), as well as blocking the memory-enhancing effect of muscle-tension-induced epinephrine release (Nielson, & Jensen, 1994). Such findings strongly indicate that glucocorticoids may selectively enhance memory consolidation for emotionally arousing material by synergistic actions of noradrenergic BLA activation, and glucocorticoids released from the adrenal cortex.

Retrieval

The administration of glucocorticoids or stress exposure that typically are associated with enhanced long-term retention also seems to impair retention if tested in close temporal proximity of the learning session (30-60 min) (Okuda et al., 2004). Likewise, stress exposure or corticosterone administered just prior to testing produces impairment of retention performance on a contextual fear conditioning task (Cai, Blundell, Han, Greene, & Powell, 2006), water maze task (Sajadi, Samaei, & Rashidy-Pour, 2006), and inhibitory avoidance task (Pakdel, & Rashidy-Pour, 2006). The impairing effect of corticosterone injections prior to retention testing on an inhibitory avoidance task is blocked by concurrent administration of propranolol (Roozendaal, de Quervain, Schelling, & McGaugh, 2004). Infusion of the GR agonist (RU 28362), or the β1-adrenoceptor agonist xamoterol into the hippocampus 60 minutes prior to testing on a water maze task learned 24 hours earlier, impairs retention performance. Concurrent infusion of the β-adrenoceptor antagonist propranolol, blocked the retrieval impairment induced by RU 28362 (Roozendaal, Hahn, Nathan, de Quervain, & McGaugh, 2004).

Studies investigating cued fear associations (Hall, Thomas, & Everitt, 2001) as well as contextual fear associations (Boujabit, Bontempi, Destrade, & Gisquet-Verrier, 2003)

have found that the retrieval of emotionally arousing material induces activation of the BLA. Glucocorticoid-induced effects on memory retrieval seem to be mediated by interactions between the BLA and the hippocampus. Infusion of the β1-adrenoceptor antagonist atenolol into the BLA or hippocampus blocks the retrieval impairment induced by a GR agonist (Roozendaal, Hahn, et al., 2004). Similarly, selective lesions of the BLA block the memory retrieval impairment induced by infusions of RU 28362 into the hippocampus 60 minutes prior to testing in a water maze task (Roozendaal, Griffith, Buranday, de Quervain, & McGaugh, 2003). These findings are consistent with the research cited previously regarding memory consolidation. Glucocorticoid-induced impairment of retrieval seems to, as is also evident in memory consolidation, depend upon activation of noradrenergic mechanisms. Furthermore, the presented findings suggest that neuronal input from the BLA, mediated by norepinephrine, enables hippocampal glucocorticoid effects on memory retrieval, and further, that this glucocorticoid-induced retrieval impairment is likely mediated, in part, by GR activation in the hippocampus.

The findings from animal studies cited above are consistent with studies investigating the effect of stress hormones on memory retrieval in humans. There is ample evidence that cortisol, either stress-induced or administered, impairs memory retrieval, especially for emotional material (e.g., Schwabe, & Wolf, 2009; Smeets et al., 2008; Tollenaar, Elzinga, Spinhoven, & Everaerd, 2009), while orally administered propranolol blocks the glucocorticoid-induced memory impairment (Schwabe et al., 2009). Buchanan and Tranel, (2008), found evidence indicating that the level of corticosteroid release in reaction to a stressor affects retrieval performance. They had participants viewing pictures with emotional and neutral content, before testing for memory 24 hours later. However, before conducting the free recall task, half of the participants were exposed to a social stressor (conducting an arithmetic task and a speech). Saliva was collected to assess cortisol levels in

all participants before being assigned to either group and was again collected after completion of the social stressor task and after the free recall task. Participants that responded to the stressor with increases in cortisol levels showed impaired retrieval performance for both emotional and neutral pictures in comparison to controls and participants in the stress condition who did not produce a cortisol response.

In a study by Tollenaar, Elzinga, Spinhoven, and Everaerd, (2008) cortisol increase induced by a psychological stress task was significantly related to decrements in retrieval performance of a word list containing both negative and neutral words, encoded five weeks prior. Interestingly, and in line with findings from animal studies suggesting that arousal may be a prerequisite for cortisol-induced memory effects, shortly after the stress task, when cortisol levels were still high but sympathetic activity had returned to baseline, cortisol increase and retrieval performance were no longer correlated. This finding, as well as findings such as those from Schwabe et al. (2009), clearly indicate that, as seems to be the case in rats, concurrent noradrenergic activation is required for stress hormone-induced effects on memory retrieval. Furthermore, functional brain imaging studies have produced findings suggesting that the retrieval of emotionally valenced information is associated with increased connectivity between the hippocampus and the amygdala (Smith, Stephan, Rugg, & Dolan, 2006). Additionally, increased activity in both the amygdala and the hippocampus has been associated with successful retrieval of emotional material studied one year later. These findings further corroborate findings from animal studies indicating that there is a significant interaction between the amygdala and hippocampus when retrieving emotionally arousing information.

Sex Differences

An exhaustive examination of sex differences is not within the scope of this review. However, as it may significantly influence the interpretation of gathered data, it is worth to highlight that gender, as well as hormonal fluctuations, might very well play a significant role in emotional memory encoding.

One study found, for example, significant differences between males and females, as well as between females in different phases of their menstrual cycle when testing for retention of gist information and peripheral detail related to a narrative story (Nielsen, Ahmed, & Cahill, 2013). Whereas men showed enhanced memory for gist, but not peripheral detail in the emotional compared with neutral stories, no enhance of gist information was evident in females. In addition, while females in the high-hormone phase of the menstrual cycle at encoding exhibited enhanced performance on peripheral detail, no such enhancement was found in women in the low-hormone phase of their cycle. Related findings revealed differences in recollection-based memory between the two phases of the menstrual cycle, and these were connected to different patterns of activity within the anterior cingulate cortex (ACC), hippocampus, and amygdala (Bayer, Schultz, Gamer, & Sommer, 2014).

Cahill, Gorski, Belcher, and Huynh (2004), found no sex-differences in recall performance of gist information and peripheral information from an emotional story. However, when the distinction between male/female was determined by scores on a psychological test designed to assess masculine and feminine traits, rather than actual sex, a significant difference was demonstrated. Furthermore, findings indicate different effects of stress-induced arousal on emotional memory for women using hormonal contraceptives (HC) and those with a natural cycle (NC). Compared to NC women, HC women displayed a decreased noradrenergic response to the images and a diminished glucocorticoid response to cold pressor stress. As both norepinephrine and cortisol interact to modulate emotional

memory, it seems likely that hormones such as endogenous estrogen and progesterone influences emotional memory modulation (Nielsen, Segal, Worden, Yim, & Cahill, 2013).

Amygdala activity associated with subsequent enhanced memory has been shown to display different patterns in men and women, with the activity of the left amygdala being correlated to enhanced memory in women, while the right amygdala is correlated to enhanced memory in men. This has been demonstrated both in studies using PET (Cahill et al., 2001) as well as fMRI imaging (Cahill, Uncapher, Kilpatrick, Alkire, & Turner, 2004).

While studies typically show that epinephrine enhances emotional memory whereas β-adrenoceptor antagonists impair it, the situation may be more complicated. One study found a significant relationship between increases in traumatic memories after cardiac surgery and the amount of epinephrine that had been administered to the patients, but critically, only in male patients. Conversely, administration of the β-adrenoceptor antagonist metoprolol selectively reduced such memories in females (Krauseneck et al., 2010).

Discussion

The aim of this thesis was to outline the impact of emotional arousal on operative processes implicated in successful memory functioning, including processes for memory formation, the strengthening of memory traces, and eventual subsequent retrieval. Further, the intent was to explain these effects from a neuroscientific point of view, using integrated findings from both human and animal studies.

The notion that emotional arousal plays a part in memory processing has been corroborated by numerous scientific studies of a various kind as well as making intuitive sense. Most of us would agree that memories with some kind of emotional significance seem to take precedence in the cramped space of our mind. At times this may have rewarding ramifications, enabling reminiscence of cherished moments long after the fact, but may also

lead to haunting intrusive recollections of events we would rather have shrouded in the opaque mist of time past.

As the research highlighted in this essay has shown, arousal affects memory in various ways. The behavioral effects stemming from emotional arousal manifest in a multitude of ways and have resulted in scientist sometimes drawing conclusions that on the surface appear to contradict one another. In the introduction section of this essay, a number of inconsistent findings were reported. Such dispersed findings, sometimes showing opposite patterns, are likely due to a combination of many factors. For example, one problem with the memory narrowing account is that most studies investigating this effect confound the central stimulus and the emotion-inducing stimulus (Levine, & Edelstein, 2009; Rush et al., 2010; Waring, & Kensinger, 2009). Usually, the emotional arousal is induced from a centrally placed stimuli of emotional valence, making it difficult to discern if arousal truly biases memory for spatially central information or if the distinctiveness of the stimuli itself captures attention, leading to subsequent enhancement of memory for that item (Laney et al., 2004). This argument could also be applied to findings from studies investigating other aspects of arousal-induced trade-off effects.

Emotional stimuli plainly benefit from capturing and holding the attention of a perceiver to a higher degree than more emotion-neutral stimuli does. This advantage appears to stem from both bottom-up processes such as perceptual contrast as well as top-down cognitive factors guiding perception and attention towards motivational relevant stimuli.

The ABC way of thinking may not provide a comprehensive explanation of arousal-induced effects on all processes with ramifications for later memory performance. Likely other factors, yet unaccounted for, such as cognitive appraisal and organization also affects this complex phenomenon. However, in the view of the author, the ABC model provides a convincing argument in resolving seemingly contradictory findings. The idea that

arousal further amplifies neural representations of such stimuli that have already, due to aspects such as perceptual saliency and motivational relevance, been given a head start in the competition for representation, neatly explains many of the findings presented in this text. Kensinger, Garoff-Eaton, et al. (2007) suggested that whether emotion impairs or enhances memory for details and gist information depends on the direction of attention during encoding. In line with this reasoning it seems *which* information is better encoded and more efficiently consolidated as a result of arousal is not a question of the *type* of information, but rather to what extent it has gained priority in neural representation. Thus, whether arousal will enhance memory for one aspect of an event at the expense of another is dependent on the circumstances relating to the event and cannot be predicted simply by a rule of thumb. If an emotional image has gained priority, post-encoding arousal will likely enhance memory for that item. On the other hand, if seemingly neutral information is deemed important, it is feasible to expect that this information will benefit from arousal-induced memory enhancement. Thus, due to the influence of such cognitive resources, the magnitude of the emotional memory effect is very sensitive to the specifics of the experimental methodology. This must be thoroughly considered when developing methodology and analyzing gathered data.

The viewing of a highly provocative image may induce arousal while the image itself will, due to its inherent properties, likely win the competition between stimuli, especially when surrounded by other items of ambiguous emotional relevance. Similarly, while paying attention to faces is something that is highly adaptive when living in a complex social milieu where successful interactions with other people are paramount, vivid remembrance of an indistinct landscape is, for most, strictly not as critical.

Epinephrine

The evidence presented here clearly indicates increases in norepinephrine (NE) levels as one of the deciding factors for observable arousal-induced memory effects. Research concerning memory consolidation has repeatedly produced convincing evidence highlighting rises in NE as an underlying component for arousal-induced memory augmentation (e.g. Jurado-Berbel et al., 2010). For example, it seems that glucocorticoid amplification of memory consolidation relies upon concurrent norepinephrine release. Further, it appears that noradrenergic activation within the basolateral amygdala (BLA) mediates the effect of epinephrine on memory consolidation (Roozendaal et al., 2006). From findings such as those, it can be inferred that the sympathoadrenal and adrenocortical systems act interactively in influencing processes of memory consolidation and indicates that adrenergic activation is a crucial component in enabling glucocorticoid augmentation of memory consolidation. Typically, drugs that impair consolidation processes also decrease levels of norepinephrine in the amygdala (Roozendaal, & McGaugh, 2011). On the other hand, the interventions commonly used in inhibitory avoidance training markedly increases the release of NE in the amygdala (Quirarte et al., 1998). Even when changing levels of NE are not under scrutiny, the influence of NE can still be inferred from studies using β-adrenoceptor antagonists such as propranolol to attenuate arousal-effects on memory.NE is also at the heart of immediate mechanisms thought to amplify the activation difference between high- and low-priority neural representations. The interactions between norepinephrine and glutamate enable increased neural transmission in relevant local sites. The neural transmission in highly active sites of representation is further amplified by positive feedback loops between NE and glutamate release, resulting from contrasting effect of NE on different adrenoreceptor subtypes (Mather et al., 2016). Further biasing processes towards that of prioritized information, the increase in NE and glutamate in these highly active regions also recruit

energy resources from nearby astrocytes, while also leading to a redirection of blood flow towards those areas and away from areas exhibiting lower activity (Toussay et al., 2013).

The Amygdala

The amygdala (AMY) has been extensively emphasized as playing a crucial role in emotion-induced memory enhancement. The presence of emotional stimuli leads to Increases in amygdala activation compared to neutral stimuli (Mitchell et al., 2008), and amygdala activation during encoding correlates with later memory for emotional material (e.g. Hamann et al., 2002). The typical finding that emotionally arousing material are better remembered than neutral information is not seen in individuals with bilateral lesions of the amygdala (Adolphs et al., 1997). Findings reviewed indicate that the amygdala impacts the way in which attention is guided by top-down goals, possibly influencing activity in the frontoparietal attention network, and amygdala activation is associated with successful encoding of emotional information in relation to neutral stimuli (Dolcos et al., 2012).

Evidence highlights that noradrenergic activation of the BLA, even in the absence of arousal stemming from a sensory experience, modulates long-term memory consolidation (Roozendaal et al., 2008). Furthermore, simultaneous noradrenergic activation of the BLA seems to be a necessary prerequisite for glucocorticoid-induced memory enhancement (Roozendaal et al., 2006). Moreover, combined findings support the idea that memory consolidation is an interactive process and that the BLA regulates processes mediated by other regions of the brain, including the caudate nucleus, hippocampus, and nucleus accumbens (Roozendaal, & McGaugh, 2011). The BLA also impacts cortical functioning in areas engaged in memory consolidation, such as the medial prefrontal cortex, while cortical cholinergic activity stemming from intact projections from the BLA to the nucleus basalis seems to be vital for BLA influences on memory consolidation. BLA also

seems to strengthen memory for events of emotional importance in part by altering specific cortical representations (Chavez et al., 2013).

The findings considered within the scope of this essay show that retrieval performance is negatively affected by heightened glucocorticoid levels in close temporal proximity to testing, while this effect is blocked by concurrent administration of propranolol (Schwabe et al., 2009). As in consolidation, glucocorticoid-induced effects on memory retrieval seem to be mediated by interactions between the BLA and the hippocampus and depend upon activation of noradrenergic mechanisms (e.g. Roozendaal, Hahn, et al., 2004).

An inherent consequence of motivationally relevant and emotional events is that people are more likely to ruminate about and discuss such occurrences after the fact. Hulse, Allan, Memon, and Read (2007) demonstrated that enhanced memory for emotional information in relation to neutral information could be established even when the opportunity for rehearsal was eliminated. Such findings illustrate that rehearsal effects cannot alone explain the memory advantage for emotional information. However, that rehearsal strengthens memory is well established (e.g., Finkenauer, Luminet, & Gisle, 1998), and thus it seems more than likely that such cognitive operations play a part in the memory advantage we experience in everyday life for emotional events.

Not explicitly examined within this text is the effect of valence direction of stimuli on subsequent memory performance. Future research may be able to delineate different arousal-induced outcomes, via stimulus-by stimulus comparison between arousal-invoking stimuli of potentially positive nature (e.g. erotic, happy) and potentially negative nature (e.g. scary, disgusting). Based on research reviewed herein, however, it seems likely that valence direction is not a determining factor. Results instead seem to imply level of

arousal as the most decisive aspect for arousal-induced memory effects, not the specific attributes of the source that was its origin (Cahill et al., 1996; Canli et al., 2000; Hamann et al., 1999; Hamann et al., 2002; Mitchell et al., 2008; Vossel et al., 2014)

A potential confound in research regarding emotional memory and arousal-induced memory effects may be innate gender differences. Future research should take in consideration the possible impact of fluctuating hormonal levels in women as well as the potential underlying differences between the sexes when interpreting results from studies investigating emotional memory and attempting to explain the sometimes inconsistent results found within this field of research. One interpretation of the findings by Cahill, Gorski et al. (2004) could be that personality traits that are commonly considered to be either feminine or masculine are somehow related to what one deems, consciously or unconsciously, to be the most essential aspects of story or situation. This is at present purely speculative, however, such findings do in the opinion of the author serve to highlight personality aspects as an underlying factor that likely influences the way an individual processes emotional information.

When developing a future experimental methodology, it is also vital to consider the inherent individual differences in reactivity. It cannot be assumed that all subjects in a study have similar physiological responses to supposedly arousing or neutral stimuli. A stimulus is not necessarily in itself neither objectively arousing nor neutral. Such distinctions are instead dependent on subjective judgments, both conscious and unconscious, by the individual and can be influenced by many factors such as prior experiences as well as genetic predisposition. Even pharmacological interventions specifically designed to manipulate arousal may have different outcomes on the individual level (e.g. Southwick, et al., 2002) and

it might thus be appropriate to contemplate the use of objective measures, such as for example norepinephrine activation when determining the operative definition of arousal.

Conclusion

Emotional arousal affects every major stage in creating, maintaining and retrieving lasting memories. Even in the earliest stages of processing, people react faster to emotional content than neutral stimuli. Emotional stimuli draw attention and are detected quicker than neutral objects due to the distinctiveness of emotional content in relation to neutral content. Research investigating memory trade-off effects induced by arousal has produced inconsistent results. This is likely due to the processes directing attention and perception toward stimuli with salient or motivational relevant features in the first place. The direction of focus is determined by both automatic bottom-up processes reacting to conspicuous stimuli and top-down processes involving the frontoparietal attention system directing selective attention towards goal-relevant information. Arousal seems to amplify this competition between stimuli, further biasing processing of neural representations that have initially gained priority.

Amygdala activation is crucial for the enhancement of memory generally associated with emotional arousal. Heightened levels of norepinephrine stemming from arousal facilitate long-term memory formation by modulating processing in the amygdala and other areas of the brain. The basolateral amygdala (BLA) projects to other brain regions, including the hippocampus, caudate nucleus, and nucleus accumbens, affecting the consolidation of different types of memories. The BLA also interacts with the medial prefrontal cortex (mPFC) in regulating memory consolidation. Furthermore, BLA activation influences cortical plasticity and may alter specific cortical representations of behaviorally important stimuli. Sympathoadrenal and adrenocortical systems act interactively in

influencing processes of memory storage. While noradrenergic activation of the BLA in isolation can modulate memory consolidation, glucocorticoid augmentation of memory consolidation appears to be dependent on concurrent adrenergic activation.

Post-encoding stress exposure or glucocorticoid administration is typically associated with enhanced long-term retention. Retrieval performance, on the other hand, is negatively affected by glucocorticoid exposure just prior to testing. This glucocorticoid-induced effect appears to depend upon activation of noradrenergic mechanisms and interactions between the hippocampus and amygdala.

References

Abercrombie, H. C., Kalin, N. H., Thurow, M. E., Rosenkranz, M. A., & Davidson, R. J. (2003). Cortisol variation in humans affects memory for emotionally laden and neutral information. *Behavioral Neuroscience, 117*(3), 506–516. doi:10.1037/0735-7044.117.3.505

Abercrombie, H. C., Speck, N. S., & Monticelli, R. M. (2006). Endogenous cortisol elevations are related to memory facilitation only in individuals who are emotionally aroused. *Psychoneuroendocrinology, 31*(2), 187–196. doi:10.1016/j.psyneuen.2005.06.008

Adolphs, R., Cahill, L., Schul, R., & Babinsky, R. (1997). Impaired declarative memory for emotional material following bilateral amygdala damage in humans. *Learning & Memory, 4*(3), 51–54. doi:10.1101/lm.4.3.291

Adolphs, R., Denburg, N. L., & Tranel, D. (2001). The amygdala's role in long-term declarative memory for gist and detail. *Behavioral Neuroscience, 115*(5), 983-992. doi:10.1037/0735-7044.115.5.983

Adolphs, R., Tranel, D., & Buchanan, T. W. (2005). Amygdala damage impairs emotional memory for gist but not details of complex stimuli. *Nature Neuroscience, 8*(4), 512-518. doi:10.1038/nn1413

Alpers, G. W., & Pauli, P. (2006). Emotional pictures predominate in binocular rivalry. *Cognition & Emotion, 20*(5), 596-607. doi:10.1080/02699930500282249

Anderson, A. K., Wais, P. E., & Gabrieli, J. D. (2006). Emotion enhances remembrance of neutral events past. *Proceedings of the National Academy of Sciences of the United States of America, 103*(5), 1599-1604. doi:10.1073/pnas.0506308103

Aston-Jones, G., & Cohen, J. (2005). Adaptive gain and the role of the locus coeruleus-norepinephrine system in optimal performance. *Journal of Comparative Neurology, 493*(1), 99-110. doi:10.1002/cne.20723

Barros, D. M., Pereira, P., Medina, J. H., & Izquierdo, I. (2002). Modulation of working memory and of long- but not short-term memory by cholinergic mechanisms in the basolateral amygdala. Behavioural Pharmacology, 13(2), 163–167. doi:10.1097/00008877-200203000-00008

Bayer, J., Schultz, H., Gamer, M., & Sommer, T. (2014). Menstrual-cycle dependent fluctuations in ovarian hormones affect emotional memory. *Neurobiology of Learning and Memory, 110*, 55-63. doi:10.1016/j.nlm.2014.01.017

Beck, D. M., & Kastner, S. (2009). Top-down and bottom-up mechanisms in biasing competition in the human brain. *Vision Research, 49*(10), 1154-1165. doi:10.1016/j.visres.2008.07.012

Bekar, L. K., Wei, H. S., & Nedergaard, M. (2012). The locus coeruleus–norepinephrine network optimizes coupling of cerebral blood volume with oxygen demand. *Journal of Cerebral Blood Flow and Metabolism, 32*(12), 2135-2145. doi:10.1038/jcbfm.2012.115

Berridge, C. W., Schmeichel, B. E., & Espana, R. A. (2012). Noradrenergic modulation of wakefulness/arousal. *Sleep Medicine Reviews, 16*(2), 187–197. doi: 10.1016/j.smrv.2011.12.003.

Berridge, C. W., & Waterhouse, B. D. (2003). The locus coeruleus–noradrenergic system: Modulation of behavioral state and state-dependent cognitive processes. *Brain Research Reviews, 42*(1), 33–84. doi:10.1016/S0165-0173(03)00143-7

Bhavin, R. S., & Thuan, P. (2008). How emotional arousal and valence influence access to awareness. *Vision Research, 48*(23), 2415-2424. doi:10.1016/j.visres.2008.07.013

Bookbinder, S. H., & Brainerd, C. J. (2017). Emotionally negative pictures enhance gist memory. *Emotion, 17*(1), 102-119. doi:10.1037/emo0000171

Bornstein, B. H., Liebel, L. M., & Scarberry, N. C. (1998). Repeated testing in eyewitness memory: A means to improve recall of a negative emotional event. *Applied Cognitive Psychology, 12*(2), 119-131. doi:10.1002/(SICI)1099-0720(199804)12:23.0.CO;2-4)

Boujabit, M., Bontempi, B., Destrade, C., & Gisquet-Verrier, P. (2003). Exposure to a retrieval cue in rats induces changes in regional brain glucose metabolism in the amygdala and other related brain structures. *Neurobiology of Learning and Memory, 79*(1), 57–71. doi:10.1016/S1074- 7427(02)00010-2

Bradley, M. M., Miccoli, L., Escrig, M. A., & Lang, P. J. (2008). The pupil as a measure of emotional arousal and autonomic activation. *Psychophysiology, 45*(4), 602-607. doi:10.1111/j.1469-8986.2008.00654.x

Buchanan, T. W., & Lovallo, W. R. (2001). Enhanced memory for emotional material following stress-level cortisol treatment in humans. *Psychoneuroendocrinology, 26*(3), 307-317. doi:10.1016/S0306-4530(00)00058-5

Buchanan, T. W., & Tranel, D. (2008). Stress and emotional memory retrieval: Effects of sex and cortisol response. *Neurobiology of Learning and Memory, 89*(2), 134-141. doi:10.1016/j.nlm.2007.07.003

Cahill, L., Gorski, L., Belcher, A., & Huynh, Q. (2004). The influence of sex versus sex-related traits on long-term memory for gist and detail from an emotional story. *Consciousness and Cognition, 13*(2), 391-400. doi:10.1016/j.concog.2003.11.003

Cahill, L., Haier, R. J., Fallon, J., Alkire, M., Tang, C., Keator, D., & . . . McGaugh, J. L. (1996). Amygdala activity at encoding correlated with long-term, free recall of emotional information. *Proceedings of the National Academy of Sciences of the United States of America, 93*(15), 8016–8021. doi:10.1073/pnas.93.15.8016

Cahill, L., Haier, R. J., White, N. S., Fallon, J., Kilpatrick, L., Lawrence, C., & . . . Alkire, M. T. (2001). Sex-related difference in amygdala activity during emotionally influenced memory storage. *Neurobiology of Learning and Memory, 75*(1), 1–9. doi:10.1006/nlme.2000.3999

Cahill, L., Uncapher, M., Kilpatrick, L., Alkire, M. T., & Turner, J. (2004). Sex-related hemispheric lateralization of amygdala function in emotionally influenced memory: An FMRI investigation. *Learning & Memory, 11*(3), 261–266. doi:10.1101/lm.70504

Cai, W. H., Blundell, J., Han, J., Greene, R. W., & Powell, C. M. (2006). Postreactivation glucocorticoids impair recall of established fear memory. *Journal of Neuroscience, 26*(37), 9560 –9566. doi:10.1523/ JNEUROSCI.2397-06.2006

Campolongo, P., Roozendaal, B., Trezza, V., Hauer, D., Schelling, G., McGaugh, J. L., & Cuomo, V. (2009). Endocannabinoids in the rat basolateral amygdala enhance memory consolidation and enable glucocorticoid modulation of memory. *Proceedings of the National Academy of Sciences of the United States of America, 106*(12), 4888–4893. doi: 10.1073/pnas.0900835106

Canli, T., Zhao, Z., Desmond, J. E., Kang, E., Gross, J., & Gabrieli, J. D. (2001). An fMRI study of personality influences on brain reactivity to emotional stimuli. *Behavioral Neuroscience, 115*(1), 33–42. doi:10.1037/ 0735-7044.115.1.33

Canli, T., Zhao, Z., Brewer, J., Gabrieli, J. D., & Cahill, L. (2000). Event-related activation in the human amygdala associates with later memory for individual emotional experience. *The Journal of neuroscience: the official journal of the Society for Neuroscience, 20*(19), 1-5. doi:10.1523/JNEUROSCI.20-19-j0004.2000

Carter, M. E., Yizhar, O., Chikahisa, S., Nguyen, H., Adamantidis, A., Nishino, S., ... & de Lecea, L. (2010). Tuning arousal with optogenetic modulation of locus coeruleus neurons. *Nature Neuroscience, 13*(12), 1526–1533. doi: 10.1038/nn.2682

Chavez, C. M., McGaugh, J. L., & Weinberger, N. M. (2009). The basolateral amygdala modulates specific sensory memory representations in the cerebral cortex. *Neurobiology of Learning and Memory, 91*(4), 382-392. doi:10.1016/j.nlm.2008.10.010

Chavez, C. M., McGaugh, J. L., & Weinberger, N. M. (2013). Activation of the basolateral amygdala induces long-term enhancement of specific memory representations in the cerebral cortex. *Neurobiology of Learning and Memory, 101,* 8-18. doi:10.1016/j.nlm.2012.12.013

Clayton, E. C., & Williams, C. L. (2000). Adrenergic activation of the nucleus tractus solitarius potentiates amygdala norepinephrine release and enhances retention performance in emotionally arousing and spatial tasks. *Behavioural Brain Research, 112*(1), 151–158. doi:10.1016/S0166- 4328(00)00178-9

de Oca, B. M., Villa, M., Cervantes, M., & Welbourne, T. (2012). Emotional modulation of the attentional blink by pleasant and unpleasant pictures. *The Journal of general psychology, 139*(4), 289-314. doi:10.1080/00221309.2012.708681

Dolcos, F., & Denkova, E. (2008). Neural correlates of encoding emotional memories: a review of functional neuroimaging evidence. *Cell Science Reviews, 5*(2), 1-45.

Dolcos, F., Denkova, E., & Dolcos, S. (2012). Neural correlates of emotional memories: a review of evidence from brain imaging studies. *Psychologia, 55*(2), 80-111. doi:10.2117/psysoc.2012.80

Donzis, E. J., & Thompson, L. T. (2014). d-Cycloserine enhances both intrinsic excitability of CA1 hippocampal neurons and expression of activity-regulated cytoskeletal (Arc) protein. *Neuroscience Letters, 571*. 50-54. doi:10.1016/j.neulet.2014.04.035

Dringenberg, H., & Vanderwolf, C. (1996). Cholinergic activation of the electrocorticogram: An amygdaloid activating system. *Experimental Brain Research, 108*(2), 285–296. doi:10.1007/BF00228101

Easterbrook, J. A. (1959). The effect of emotion on cue utilization and the organization of behavior. *Psychological Review, 66*(3), 183-201

Egli, R. E., Kash, T. L., Choo, K., Savchenko, V., Matthews, R. T., Blakely, R. D., & Winder, D. G. (2005). Norepinephrine modulates glutamatergic transmission in the bed nucleus of the stria terminalis. *Neuropsychopharmacology, 30*(4), 657– 668. doi:10.1038/sj.npp.1300639

Fawcett, J. M., Russel, E. J., Peace, K. A., & Christie, J. (2013). Of guns and geese: a meta-analytic review of the 'weapon focus' literature. *Psychology, Crime, & Law, 19*(1) 35-66. doi:10.1080/1068316X.2011.599325

Finkenauer, C., Luminet, O., & Gisle, L. (1998). Flashbulb memories and the underlying mechanisms of their formation: Toward an emotional-integrative model. *Memory & Cognition, 26*(3), 516-531. doi:10.3758/BF03201160

Freeman, A. W., & Nguyen, V. A. (2001). Controlling binocular rivalry. *Vision research, 41*(23), 2943-50. doi:10.1016/S0042-6989(01)00181-X

Gazzaley, A., Cooney, J. W., McEvoy, K., Knight, R. T., & D'Esposito, M. (2005). Top-down enhancement and suppression of the magnitude and speed of neural activity.

Journal of Cognitive Neuroscience, 17(3), 507-517. doi:10.1162/0898929053279522

Gazzaniga, M. S., Ivry, R. B., & Mangun, G. R. (2014). *The Biology of the Mind* (4). New York: W. W. Norton & Company.

Gold, P. E., & Van Buskirk, R. B. V. (1975). Facilitation of time-dependent memory processes with posttrial epinephrine injections. *Behavioral Biology, 1*3(2), 145-153. doi:10.1016/S0091-6773(75)91784-8

Guillet, R., & Arndt, J. (2009). Taboo words: The effect of emotion on memory for peripheral information. *Memory & Cognition, 3*7(6), 866–879. doi:10.3758/MC.37.6.866

Hall, J., Thomas, K. L., & Everitt, B. J. (2001). Cellular imaging of zif 268 expression in the hippocampus and amygdala during contextual and cued fear memory retrieval: Selective activation of hippocampal CA1 neurons during recall of contextual memory. *Journal of Neuroscience, 2*1(6), 2186–2193.

Hamann, S. B., Eli, T. D., Grafton, S. T., & Kilts, C. D. (1999). Amygdala activity related to enhanced memory for pleasant and aversive stimuli. *Nature Neuroscience, 2*(3), 289–303. doi:10.1038/6404

Hamann, S. B., Eli, T. D., Hoffman, J. M., & Kilts, C. D. (2002). Ecstacy and agony: Activation of the human amygdala in positive and negative emotions. *Psychological Science*, *13*(2), 135–141. doi:10.1111/1467- 9280.00425

Huff, N. C., Wright-Hardesty, K. J., Higgins, E. A., Matus-Amat, P., & Rudy, J. W. (2005). Context pre-exposure obscures amygdala modulation of contextual-fear conditioning. *Learning & Memory, 12*(5), 456–460. doi:10.1101/lm.6705

Hulse, L. M., Allan, K., Memon, A., & Read, J. D. (2007). Emotional Arousal and Memory: A Test of the Poststimulus Processing Hypothesis. *The American Journal of Psychology, 120(1), 73-90. doi:10.2307/20445382*

Hurlemann, R., Hawellek, B., Matusch, A., Kolsch, H., Wollersen, H., Madea, B., & ... Dolan, R. J. (2005). Noradrenergic modulation of emotion-induced forgetting and remembering. *Journal of Neuroscience, 25*(27), 6343–6349. doi:10.1523/JNEUROSCI.0228-05.2005

Introini-Collison, I. B., Saghafi, D., Novack, G., & McGaugh, J. L. (1992). Memory-enhancing effects of posttraining dipivefrin and epinephrine: Involvement of peripheral and central adrenergic receptors. *Brain Research, 572*(1-2), 81–86. doi:10.1016/0006-8993(92)90454-H

Joëls, M., & Baram, T. Z. (2009). The neuro-symphony of stress. *Nature Reviews Neuroscience, 10*(6), 459-466. doi:10.1038/nrn2632

Joëls, M., Fernandez, G., & Roozendaal, B. (2011). Stress and emotional memory: A matter of timing. *Trends in Cognitive Science, 15*(6), 280–288. doi:10.1016/j.tics.2011.04.004

Johnson, M. R., & Johnson, M. K. (2009). Top-down enhancement and suppression of activity in category-selective extrastriate cortex from an act of reflective attention. *Journal of Cognitive Neuroscience, 21*(12), 2320-2327. doi:10.1162/jocn.2008.21183

Jurado-Berbel, P., Costa-Miserachs, D., Torras-Garcia, M., Coll-Andreu, M., & Portell-Cortes, I. (2010). Standard object recognition memory and ‘‘what’’ and ‘‘where’’ components: Improvement by post-training epinephrine in highly habituated rats. *Behavioural Brain Research, 207*(1), 44–50. doi:10.1016/j.bbr.2009.09.036

Kensinger, E. A., Garoff-Eaton, R. J., & Schacter, D. L. (2006). Memory for specific visual details can be enhanced by negative arousing content. *Journal of Memory and Language, 54*(1), 99-112. doi:10.1016/j.jml.2005.05.005

Kensinger, E. A., Garoff-Eaton, R. J., & Schacter, D. L. (2007). Effects of emotion on memory specificity: Memory trade-offs elicited by negative visually arousing stimuli. *Journal of Memory and Language, 56*(4), 575–591. doi:10.1016/j.jml.2006.05.004

Kensinger, E. A., Gutchess, A. H., & Schacter, D. L. (2007). Effects of aging and encoding instructions on emotion-induced memory trade-offs. Psychology and Aging, 22(4), 781-795. doi:10.1037/0882-7974.22.4.781

Kensinger, E. A., & Schacter, D. L. (2006). Amygdala activity is associated with the successful encoding of item, but not source, information for positive and negative stimuli. *Journal of Neuroscience, 26*(9), 2564–2570. doi:10.1523/JNEUROSCI.5241-05.2006

Keren, N. I., Lozar, C. T., Harris, K. C., Morgan, P. S., & Eckert, M. A. (2009). In vivo mapping of the human locus coeruleus. *Neuroimage, 47*(4), 1261-1267. doi:10.1016/j.neuroimage.2009.06.012

Kissler, J., Herbert, C., Peyk, P., & Junghofer, M. (2007). Buzzwords: Early Cortical Responses to Emotional Words During Reading. *Psychological science, 18*(6), 475-480. doi:10.1111/j.1467-9280.2007.01924.x

Knight, M., & Mather, M. (2009). Reconciling findings of emotion- induced memory enhancement and impairment of preceding items. *Emotion, 9*(6), 763–781. doi:10.1037/a0017281

Knight, M., Seymour, T. L., Gaunt, J. T., Baker, C., Nesmith, K., & Mather, M. (2007). Aging and Goal-Directed Emotional Attention: Distraction Reverses Emotional Biases. *Emotion, 7*(4), 705–714. doi:10.1037/1528-3542.7.4.705

Kobayashi, M., Kojima, M., Koyanagi, Y., Adachi, K., Imamura, K., & Koshikawa, N. (2009) Presynaptic and postsynaptic modulation of glutamatergic synaptic transmission by activation of α1- and β-adrenoceptors in layer V pyramidal neurons of rat cerebral cortex. *Synapse, 63*(4), 269–281. doi:10.1002/syn.20604

Krauseneck, T., Padberg, F., Roozendaal, B., Grathwohl, M., Weis, F., Hauer, D., & . . . Schelling, G. (2010). A beta-adrenergic antagonist reduces traumatic memories and PTSD symptoms in female but not in male patients after cardiac surgery. *Psychological Medicine, 40*(5), 861–869. doi:10.1017/S0033291709990614

Krugers, H. J., Karst, H., & Joels, M. (2012). Interactions between noradrenaline and corticosteroids in the brain: from electrical activity to cognitive performance. Frontiers in Cellular Neuroscience, 6(15), 1-10. doi:10.3389/fncel.2012.00015

LaLumiere, R. T., Buen, T.-V., & McGaugh, J. L. (2003). Posttraining intra-basolateral amygdala infusions of norepinephrine enhance consolidation of memory for contextual fear conditioning. *Journal of Neuroscience, 23*(17), 6754–6758.

LaLumiere, R. T., Nguyen, L., & McGaugh, J. L. (2004). Posttraining intra-basolateral amygdala infusions of dopamine modulate consolidation of inhibitory avoidance memory: Involvement of noradrenergic and cholinergic systems. *European Journal of Neuroscience, 20*(10), 2804– 2810. doi:10.1111/j.1460-9568.2004.03744.x

Laney, C., Campbell, H. V., Heuer, F., & Reisberg, D. (2004). Memory for thematically arousing events. *Memory and Cognition*, *32*(7), 1149-1159

Langer, S. Z. (2008). Presynaptic autoreceptors regulating transmitter release. *Neurochemistry International, 52*(1/2), 26–30. doi:10.1016/j.neuint.2007.04.031

Lee, K. Y., Lee, T. H., Yoon, S. J., Cho, Y. S., Choi, J. S., & Kim, T. H. (2010). Neural correlates of top–down processing in emotion perception: An ERP study of emotional faces in white noise versus noise-alone stimuli. *Brain Research, 1337*, 56-63. doi:10.1016/j.brainres.2010.03.094

Lee, T. H., Sakaki, M., Cheng, R., Velasco, R., & Mather, M. (2014). Emotional arousal amplifies the effects of biased competition in the brain. Social Cognitive and Affective Neuroscience, 9(12), 2067–2077. doi:10.1093/scan/nsu015

Levine, L., & Edelstein, R. (2009). Emotion and memory narrowing : A review and goal-relevance approach. *Cognition and Emotion, 23*(5), 833-875. doi:10.1080/02699930902738863

Liang, K. C., Hu, S.-J., & Chang, S. H. (1996). Formation and retrieval of inhibitory avoidance memory: Differential roles of glutamate receptors in the amygdala and medial prefrontal cortex. *Chinese Journal of Physiology, 39*(3), 155–166.

Liang, K. C., Juler, R. G., & McGaugh, J. L. (1986). Modulating effects of post-training epinephrine on memory: Involvement of the amygdala noradrenergic system. *Brain Research, 368*(1), 125–133. doi:10.1016/ 0006-8993(86)91049-8

Libkuman, T. M., Nichols-Whitehead, P., Griffith, J., & Thomas, R. (1999). Source of arousal and memory for detail. *Memory & Cognition, 27*(1), 166-190. doi:10.3758/BF03201222

Lim, S. L., Padmala, S., & Pessoa, L. (2009). Segregating the significant from the mundane on a moment-to-moment basis via direct and indirect amygdala contributions. *Proceedings of the National Academy of Sciences of the United States of America, 106*(39), 16841-16846. doi:10.1073/pnas.0904551106

Liu, T. T. (2012). The development of event-related fMRI designs. *Neuroimage, 62*(2), 1157-1162. doi:10.1016/j.neuroimage.2011.10.008

Liu, D. L. J., Graham, S., & Zorawski, M. (2008). Enhanced selective memory consolidation following post-learning pleasant and aversive arousal. *Neurobiology of Learning and Memory, 89*(1), 36-46. doi:10.1016/j.nlm.2007.09.001

Loftus, L. F., Loftus, G. R., & Messo, J. (1987). Some facts about weapon focus. *Law and Human Behavior, 11*(1) 55-62. 10.1007/BF01044839

Madan, C. R., Caplan, J. B., Christine, S. M., Lau, C. S. M., & Fujiwara, E. (2012). Emotional arousal does not enhance association-memory. *Journal of Memory and Language, 66*(4), 695-716. doi:10.1016/j.jml.2012.04.001

Madan, C. R., Fujiwara, E., Caplan, J. B., & Sommer, T. (2017). Emotional arousal impairs association-memory: Roles of amygdala and hippocampus. *Neuroimage, 156*, 14-28. doi:10.1016/j.neuroimage.2017.04.065

Marzo, A., Bai, J., & Otani, S. (2009). Neuroplasticity regulation by noradrenaline in mammalian brain. *Current Neuropharmacology, 7*(4), 286-295. doi:10.2174/157015909790031193

Mather, M., Clewett, D., Sakaki, M., & Harley, C. W. (2016). Norepinephrine ignites local hotspots of neuronal excitation: How arousal amplifies selectivity in perception and memory. *Behavioral and Brain Sciences, 39*(200), 1-75. doi:10.1017/S0140525X15000667

Mather, M., & Sutherland, M. R. (2009). Disentangling the effects of arousal and valence on memory for intrinsic details. *Emotion Review, 1*(2), 118-119. doi:10.1177/1754073908100435

Mather, M., & Sutherland, M. R. (2011). Arousal-Biased Competition in Perception and Memory. *Perspectives on Psychological Science*, *6*(2) 114–133. doi:10.1177/1745691611400234

McGaugh, J. L., Cahill, L., & Roozendaal, B. (1996). Involvement of the amygdala in memory storage: Interaction with other brain systems. *Proceedings of the National Academy of Sciences of the United States of America, 93*(24), 13508-13514. doi:10.1073/pnas.93.24.13508

McIntyre, C. K., Hatfield, T., & McGaugh, J. L. (2002). Amygdala norepinephrine levels after training predict inhibitory avoidance retention performance in rats. *European Journal of Neuroscience, 16*(7), 1223– 1226. doi:10.1046/j.1460-9568.2002.02188.x

McIntyre, C. K., Miyashita, T., Setlow, B., Marjon, K. D., Steward, O., Guzowski, J. F., & McGaugh, J. L. (2005). Memory-influencing intra- basolateral amygdala drug infusions modulate expression of arc protein in the hippocampus. *Proceedings of the National Academy of Sciences of the United States of America, 102*(30), 10718–10723. doi:10.1073/ pnas.0504436102

Miendlarzewska, E. A., Bavelier, D., & Schwartz, S. (2016). Influence of reward motivation on human declarative memory. *Neuroscience and Biobehavioral Reviews, 61*, 156-176. doi:10.1016/j.neubiorev.2015.11.015

Mitchell, D. G. V., Luo, Q., Mondillo, K., Vythilingam, M., Finger, E. C., & Blair, R. J. R. (2008). The interference of operant task performance by emotional distracters: An antagonistic relationship between the amygdala and frontoparietal cortices. *NeuroImage, 40*(2), 859-868. doi:10.1016/j.neuroimage.2007.08.002

Morgan, C. A., Hazlett, G., Doran, A., Garrett, S., Hoyt, G., Thomas, P., & ... Southwick, S. M. (2004). Accuracy of eyewitness memory for persons encountered during exposure to highly intense stress. *International Journal of Law and Psychiatry, 27*(3), 265-279. doi:10.1016/j.ijlp.2004.03.004

Murugaiah, K. D., & O'Donnell, J. M. (1995). Facilitation of norepinephrine release from cerebral cortex is mediated by β2-adrenergic receptors. *Life Sciences, 57*(20), 327-332. doi:10.1016/0024-3205(95)02173-G

Nashiro, K., & Mather, M. (2011). How arousal affects younger and older adults' memory binding. *Experimental Aging Research, 37*(1), 108-128. doi:10.1080/0361073X.2011.536746

Nielsen, S. E., Ahmed, I., & Cahill, L. (2013). Sex and menstrual cycle phase at encoding influence emotional memory for gist and detail. *Neurobiology of Learning and Memory, 106*, 56-65. doi:10.1016/j.nlm.2013.07.015

Nielson, K. A., & Jensen, R. A. (1994). Beta-adrenergic receptor antagonist antihypertensive medications impair arousal-induced modulation of working memory in elderly humans. *Behavioral and Neural Biology, 62*(3), 190–200. doi:10.1016/S0163-1047(05)80017-2

Nielson, K. A., & Powless, M. (2007). Positive and negative sources of emotional arousal enhance long-term word-list retention when induced as long as 30 min after learning. *Neurobiology of Learning and Memory*, *88*(1), 40-47. doi:10.1016/j.nlm.2007.03.005

Nielsen, S. E., Segal, S. K., Worden, I. V., Yim, I. S., & Cahill, L. (2013). Hormonal contraception use alters stress responses and emotional memory. *Biological Psychology*, *92*(2), 257-266. doi:10.1016/j.biopsycho.2012.10.007

Nothdurft, H. C. (2000). Salience from feature contrast: additivity across dimensions. *Vision Research, 40*(10), 1183–1201. doi:10.1016/S0042-6989(00)00031-6

Nummenmaa, L., Hyönä, J., & Calvo, M. G. (2006). Eye Movement Assessment of Selective Attentional Capture by Emotional Pictures. *Emotion, 6*(2), 257–268. doi:10.1037/1528-3542.6.2.257

O'Carroll, R. E., Drysdale, E., Cahill, L., Shajahan, P., & Ebmeier, K. P. (1999). Stimulation of the noradrenergic system enhances and blockade reduces memory for emotional material in man. *Psychological Medicine, 29*(5), 1083–1088. doi:10.1017/S0033291799008703

O'Donnell, J., Zeppenfeld, D., McConnell, E., Pena, S., & Nedergaard, M. (2012). Norepinephrine: A neuromodulator that boosts the function of multiple cell types to optimize CNS performance. *Neurochemical Research, 37*(11), 2496– 2512. doi:10.1007/s11064-012-0818-x

Okubo, Y., Sekiya, H., Namiki, S., Sakamoto, H., Iinuma, S., Yamasaki, M., & ... Iino, M. (2010). Imaging extrasynaptic glutamate dynamics in the brain. *Proceedings of the National Academy of Sciences of the United States of America, 107*(14), 6526-6531. doi:10.1073/pnas.0913154107

Okuda, S., Roozendaal, B., & McGaugh, J. L. (2004). Glucocorticoid effects on object recognition memory require training-associated emotional arousal. *Proceedings of the National Academy of Sciences of the United States of America, 101*(3), 853–858. doi:10.1073/pnas.0307803100

Orsten-Hooge, K. D., Portillo, M. C., & Pomerantz, J. R. (2015). False Pop Out. *Journal of experimental psychology. Human perception and performance, 41*(6), 1623-1633. doi:10.1037/xhp0000077

Otani, H., Libkuman, T. M., Widner, R. L., & Graves, E. I. (2007). Memory for Emotionally Arousing Stimuli: A Comparison of Younger and Older Adults. *The Journal of General Psychology, 134*(1), 23-42. doi:0.3200/GENP.134.1.23-42

Packard, M. G., & Cahill, L. (2001). Affective modulation of multiple memory systems. *Current Opinion in Neurobiology, 1*1(6), 752–756. doi:10.1016/S0959-4388(01)00280-X

Packard, M. G., & Teather, L. (1998). Amygdala modulation of multiple memory systems: Hippocampus and caudate-putamen. *Neurobiology of Learning and Memory, 69*(2), 163–203. doi:10.1006/nlme.1997.3815

Pakdel, R., & Rashidy-Pour, A. (2006). Glucocorticoid-induced impairment of long-term memory retrieval in rats: An interaction with dopamine D2 receptors. *Neurobiology of Learning and Memory, 85*(3), 300– 306. doi:10.1016/j.nlm.2005.12.003

Parent, M. B., & McGaugh, J. L. (1994). Posttraining infusion of lidocaine into the amygdala basolateral complex impairs retention of inhibitory avoidance training. *Brain Research, 661*(1-2), 97–103. doi:10.1016/0006- 8993(94)91186-X

Payne, J. D., Nadel, L., Allen, J .J. B., Thomas, K. G. F., & Jacobs, W. J. (2002). The effects of experimentally induced stress on false recognition. *Memory, 10*(1), 1–6. doi:10.1080/09658210143000119

Power, A. E., Thal, L. J., & McGaugh, J. L. (2002). Lesions of the nucleus basalis magnocellularis induced by 192 IgG-saporin block memory enhancements with posttraining norepinephrine in the basolateral amygdala. *Proceedings of the National Academy of Sciences of the United States of America, 99*(4), 2325–2329. doi:10.1073/pnas.022627799

Quirarte, G. L., Galvez, R., Roozendaal, B., & McGaugh, J. L. (1998). Norepinephrine release in the amygdala in response to footshock and opioid peptidergic drugs. Brain Research, 808(2), 134–140. doi:10.1016/ S0006-8993(98)00795-1

Rajimehr, R., Devaney, K., Bilenko, N. Y., Young, J. C., & Tootell, R. B. H. (2011). The "parahippocampal place area" responds preferentially to high spatial frequencies in humans and monkeys. *Plos Biology, 9*(4), 1-11. doi:10.1371/journal.pbio.1000608

Ramos, B. P., & Arnsten, A. F. T. (2007). Adrenergic pharmacology and cognition: Focus on the prefrontal cortex. *Pharmacology and Therapeutics, 113*(3), 523– 536. doi:10.1016/j.pharmthera.2006.11.006

Rinne, A., Birk, A., & Bünemann, M. (2013). Voltage regulates adrenergic receptor function. *Proceedings of the National Academy of Sciences of the United States of America, 110*(4), 1536–1541. doi:10.1073/pnas.1212656110

Ritchey, M., Dolcos, F., & Cabeza, R. (2008). Role of Amygdala Connectivity in the Persistence of Emotional Memories Over Time: An Event-Related fMRI Investigation. *Cerebral Cortex, 18*(11), 2494–2504. doi:10.1093/cercor/bhm262

Roesler, R., Roozendaal, B., & McGaugh, J. L. (2002). Basolateral amygdala lesions block the memory-enhancing effect of 8-Br-cAMP infused into the entorhinal cortex of rats after training. *European Journal of Neuroscience, 15*(5), 905–910. doi:10.1046/j.1460-9568.2002.01924.x

Roozendaal, B., Carmi, O., & McGaugh, J. L. (1996). Adrenocortical suppression blocks the memory-enhancing effects of amphetamine and epinephrine. *Proceedings of the National Academy of Sciences of the United States of America, 93*(4), 1429–1433. doi:10.1073/pnas.93.4.1429

Roozendaal, B., Castello, N. A., Vedana, G., Barsegyan, A., & McGaugh, J. L. (2008). Noradrenergic activation of the basolateral amygdala modulates consolidation of object recognition memory. *Neurobiology of Learning and Memory, 90*(3), 576–579. doi:10.1016/j.nlm.2008.06.010

Roozendaal, B., de Quervain, D. J. F., Schelling, G., & McGaugh, J. L. (2004). A systemically administered beta-adrenoceptor antagonist blocks corticosterone-induced impairment of contextual memory retrieval in rats. *Neurobiology of Learning and Memory, 81*(2), 150–154. doi:10.1016/ j.nlm.2003.10.001

Roozendaal, B., Griffith, Q. K., Buranday, J., de Quervain, D. J. F., & McGaugh, J. L. (2003). The hippocampus mediates glucocorticoid- induced impairment of spatial memory retrieval: Dependence on the basolateral amygdala. *Proceedings of the National Academy of Sciences of the United States of America, 100*(3), 1328–1333. doi:10.1073/ pnas.0337480100

Roozendaal, B., Hahn, E. L., Nathan, S. V., de Quervain, D. J. F., & McGaugh, J. L. (2004). Glucocorticoid effects on memory retrieval require concurrent noradrenergic activity in the hippocampus and basolateral amygdala. *Journal of Neuroscience, 24*(37), 8161–8169. doi:10.1523/ JNEUROSCI.2574-04.2004

Roozendaal, B., & McGaugh, J. L. (1997). Basolateral amygdala lesions block the memory-enhancing effect of glucocorticoid administration in the dorsal hippocampus of rats. *European Journal of Neuroscience, 9*(1), 76–83. doi:10.1111/j.1460-9568.1997.tb01355.x

Roozendaal, B., & McGaugh, J. L. (2011). Memory modulation. *Behavioral Neuroscience, 125*(6), 797-824. doi:10.1037/a0026187

Roozendaal, B., McReynolds, J. R., Van der Zee, E. A., Lee, S., McGaugh, J. L., & McIntyre, C. K. (2009). Glucocorticoid effects on memory consolidation depend on functional interactions between the medial prefrontal cortex and basolateral amygdala. *Journal of Neuroscience, 29*(45), 14299–14308. doi:10.1523/JNEUROSCI.3626-09.2009

Roozendaal, B., Okuda, S., Van der Zee, E., & McGaugh, J. (2006). Glucocorticoid enhancement of memory requires arousal-induced noradrenergic activation in the basolateral amygdala. *Proceedings of the National Academy of Sciences of the United States of America, 103*(17), 6741-6746. doi:10.1073/pnas.0601874103

Roozendaal, B., Portillo-Marquez, G., & McGaugh, J. L. (1996). Basolateral amygdala lesions block glucocorticoid-induced modulation of memory for spatial learning. *Behavioral neuroscience, 110*(5), 1074-1083. doi:10.1037/0735-7044.110.5.1074

Rosler, A., Ulrich, C., Billino, J., Sterzer, P., Weidauer, S., Bernhardt, T., & … Kleinchmidt, A. (2005). Effects of arousing emotional scenes on the distribution of visuospatial attention: changes with aging and early subcortical vascular dementia. *Journal of the Neurological Sciences, 229*, 109–116. doi:10.1016/j.jns.2004.11.007

Rush, E. B., Quas, J. A., & Yim, I. S. (2010). Memory narrowing in children and adults. *Applied Cognitive Psychology, 25*(6), 841-849. doi:10.1002/acp.1757

Sajadi, A. A., Samaei, S. A., & Rashidy-Pour, A. (2006). Intra- hippocampal microinjections of anisomycin did not block glucocorticoid-induced impairment of memory retrieval in rats: An evidence for non-genomic effects of glucocorticoids. *Behavioral Brain Research, 173*(1), 158–162. doi:10.1016/j.bbr.2006.06.018

Sandi, C., & Pinelo-Nava, M. T. (2007). Stress and memory: Behavioral effects and neurobiological mechanisms. *Neural Plasticity, 2007*, 1-20. doi:10.1155/2007/78970

Sandrini, M., Cohen, L. G., & Censor, N. (2015). Modulating reconsolidation: a link to causal systems-level dynamics of human memories. *Trends in Cognitive Sciences, 19*(5), 475-482.

Sara, S. J., & Bouret, S. (2012). Orienting and reorienting: The locus coeruleus mediates cognition through arousal. *Neuron, 76*(1):130–1341. doi:10.1016/j.neuron.2012.09.011

Schmidt, S. R., & Saari, B. (2007). The emotional memory effect: Differential processing or item distinctiveness? *Memory & Cognition, 35*(8), 1905-1916. doi:10.3758/BF03192924

Schwabe, L., Bohringer, A., Chatterjee, M., & Schachinger, H. (2008). Effects of pre-learning stress on memory for neutral, positive and negative words: different roles of cortisol and autonomic arousal. *Neurobiology of Learning and Memory, 90*(1), 44-53. doi:10.1016/j.nlm.2008.02.002

Schwabe, L., Joëls, M., Roozendaal, B., Wolf, O. T., & Oitzl, M. S. (2012). Stress effects on memory: An update and integration. *Neuroscience & Biobehavioral Reviews, 36*(7), 1740-1749. doi:10.1016/j.neubiorev.2011.07.002

Schwabe, L., Römer, S., Richter, S., Dockendorf, S., Bilak, B., & Schachinger, H. (2009). Stress effects on declarative memory retrieval are blocked by a beta-adrenoceptor antagonist in humans. *Psychoneuroendocrinology, 34*(3), 446–454. doi:10.1016/j.psyneuen.2008.10.009

Schwabe, L., & Wolf, O. T. (2009). The context counts: Congruent learning and testing environments prevent memory retrieval impairment following stress. *Cognitive Affective and Behavioral Neuroscience, 9*(3), 229–236. doi:10.3758/CABN.9.3.229

Segal, S. k., & Cahill, L. (2009). Endogenous noradrenergic activation and memory for emotional material in men and women. *Psychoneuroendocrinology, 34*(9), 1263-1271. doi:10.1016/j.psyneuen.2009.04.020

Sergerie, K., Lepage, M., & Armony, J. L. (2006). A process-specific functional dissociation of the amygdala in emotional memory. *Journal of Cognitive Neuroscience, 18*(8), 1359–1367. doi:10.1162/jocn.2006.18.8.1359

Setlow, B., Roozendaal, B., & McGaugh, J. L. (2000). Involvement of a basolateral amygdala complex–nucleus accumbens pathway in glucocorticoid-induced modulation of memory storage. *European Journal of Neuroscience, 12*(1), 367– 375. doi:10.1046/j.1460-9568.2000.00911.x

Shapiro, K. L., Raymond, J. E., & Arnell, K. M. (1997). The attentional blink. Trends in Cognitive Sciences, 1(8), 291-296. doi:10.1016/S1364-6613(97)01094-2

Smeets, T., Otgaar, H., Candel, I., & Wolf, O. T. (2008). True or false? Memory is differentially affected by stress-induced cortisol elevations and sympathetic activity at consolidation and retrieval. *Psychoneuroendocrinology, 33*(10), 1378–1386. doi:10.1016/j.psyneuen.2008.07.009

Smith, A. P., Stephan, K. E., Rugg, M. D., & Dolan, R. J. (2006). Task and content modulate amygdala-hippocampal connectivity in emotional retrieval. *Neuron, 49*(4), 631–638. doi:10.1016/j.neuron.2005.12.025

Soetens, E., Casaer, S., D'Hooge, R., & Hueting, J. E. (1995). Effect of amphetamine on long-term retention of verbal material. *Psychopharmacology, 119*(2), 155–162. doi:10.1007/BF02246156

Southwick, S., Davis, M., Horner, B., Cahill, L., Morgan, D., Gold, P., ... & Charney, D. (2002). Relationship of enhanced norepinephrine activity during memory consolidation to enhanced long-term memory in humans. *American Journal of Psychiatry, 159*(8), 1420–1422. doi:10.1176/ appi.ajp.159.8.1420

Stefanucci, J. K., & Storbeck, J. (2009). Don't Look Down: Emotional Arousal Elevates Height Perception. *Journal of Experimental Psychology: General, 138*(1), 131–145. doi:10.1037/a0014797

Strange, B. A., & Dolan, R. J. (2004). Beta-adrenergic modulation of emotional memory-evoked human amygdala and hippocampal responses. *Proceedings of the National Academy of Sciences of the United States of America, 101*(31), 11454–11458. doi:10.1073/pnas.0404282101

Strange, B. A., Hurlemann, R., & Dolan, R. J. (2003). An emotion-induced retrograde amnesia in humans is amygdala- and beta-adrenergic-dependent. *Proceedings of the National Academy of Sciences of the United States of America,100*(23), 13626–13631. doi:10.1073/pnas.1635116100

Talmi, D. (2013). Enhanced Emotional Memory: Cognitive and Neural Mechanisms. *Current Directions in Psychological Science, 22*(6), 430-436. doi:10.1177/0963721413498893

Tollenaar, M. S., Elzinga, B. M., Spinhoven, P., & Everaerd, W. A. (2008). The effects of cortisol increase on long-term memory retrieval during and after acute psychosocial stress. *Acta Psychologia (Amsterdam), 127*(3), 542–552. doi:10.1016/j.actpsy.2007.10.007

Tollenaar, M. S., Elzinga, B. M., Spinhoven, P., & Everaerd, W. A. (2009). Immediate and prolonged effects of cortisol, but not propranolol, on memory retrieval in healthy young men. *Neurobiology of Learning and Memory, 91*(1), 23–31. doi:10.1016/j.nlm.2008.08.002

Toussay, X., Basu, K., Lacoste, B., & Hamel, E. (2013). Locus coeruleus stimulation recruits a broad cortical neuronal network and increases cortical perfusion. *The Journal of Neuroscience, 33*(8), 3390–3401. doi:10.1523/JNEUROSCI.3346-12.2013

Traynelis, S. F., Wollmuth, L. P., McBain, C. J., Menniti, F. S., Vance, K. M., Ogden, K., & ... Dingledine, R. (2010). Glutamate receptor ion channels: Structure, regulation, and function. *Pharmacological Reviews, 62*(3), 405–496. doi:10.1124/pr.109.002451

Van Stegeren, A. H. (2008). The role of the noradrenergic system in emotional memory. *Acta Psychologia, 127*(3), 532–541. doi:10.1016/j.actpsy.2007.10.004

Van Stegeren, A. H., Roozendaal, B., Kindt, M., Wolf, O. T., & Joëls, M. (2010). Interacting noradrenergic and corticosteroid systems shift human brain activation patterns during encoding. *Neurobiology of Learning and Memory, 93*(1), 56–65. doi:10.1016/j.nlm.2009.08.004

Vossel, S., Geng, J. J., & Fink, G. R. (2014). Dorsal and Ventral Attention Systems: Distinct Neural Circuits but Collaborative Roles. *The Neuroscientist, 20*(2), 150-159. doi:10.1177/1073858413494269

Wang, Z., & McCormick, D. A. (1993). Control of firing mode of corticotectal and corticopontine layer V burst-generating neurons by norepinephrine, acetylcholine, and 1S,3R-ACPD. *The Journal of Neuroscience, 13*(5), 2199–2216. doi:10.1523/JNEUROSCI.13-05-02199.1993

Waring, J. D., & Kensinger, E. A. (2009). Effects of emotional valence and arousal upon memory trade-offs with aging. *Psychology and Aging, 24*(2), 412–422. doi:10.1037/a0015526

Weinberger, N. M. (2007). Associative representational plasticity in the auditory cortex: a synthesis of two disciplines. *Learning & Memory, 14*(1–2), 1-16. doi:10.1101/lm.421807

Williams, C. L., Men, D., Clayton, E. C., & Gold, P. E. (1998). Norepinephrine release in the amygdala after systemic injections of epinephrine or inescapable footshock: Contribution of the nucleus of the solitary tract. *Behavioral Neuroscience, 112*(6), 1414–1422. doi:10.1037/0735- 7044.112.6.1414

Zald, D. H., & Pardo, J. V. (2002). The Neural Correlates of Aversive Auditory Stimulation. *NeuroImage, 16*(3), 746-753. doi:10.1006/nimg.2002.1115

Öhman, A., Flykt, A., & Esteves, F. (2001). Emotion drives attention: Detecting the snake in the grass. *Journal of Experimental Psychology: Genera*l, 130(3), 466–478.