SAVORING POSITIVE EMOTIONS: COPING WITH NEGATIVE AFFECT IN THE PRESENT AND FROM THE PAST

by

MEGAN ELIZABETH SPEER

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Written under the direction of Professor Mauricio R. Delgado

and approved by:

Dr. Mauricio R. Delgado

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Dr. Vanessa LoBue

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Dr. Daniela Schiller

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Dr. Elizabeth Tricomi

_____

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ABSTRACT OF THE DISSERTATION

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by Megan Elizabeth Speer

Dissertation Director: Dr. Mauricio R. Delgado

The ability to regulate emotion under stressful circumstances is a crucial component of resilient coping and healthy psychological wellbeing. However, typical strategies aimed at dampening negative emotions (e.g., suppression) are not effective for everyone or in all contexts, suggesting a critical need for alternative forms of coping. One potential alternative is to focus on increasing positive feelings instead. Bolstering positive emotion can broaden one's scope of cognition and help build psychological resources for coping with future adversity. Thus, the overarching goal of this dissertation was to examine whether positive emotion-focused coping could counter negative affect occurring in the present moment (e.g., experiencing acute stress) and stemming from past adversity (e.g., remembering negative memories). In Experiments 1-2, we found that enhancing positive emotions via positive reminiscence successfully reduced two detrimental consequences of acute stress exposure—stress hormone levels (i.e., cortisol) and negative mood. Using fMRI, positive reminiscence also engaged neural circuitry linked to emotion regulation (DLPFC, VLPFC) and reward-processing (striatum, MFPC), suggesting its emotion regulatory function. In Experiments 3-7, we then tested whether finding positive meaning

in past negative events could adaptively update our memories, changing how we feel (emotion elicited by the memory) and what we remember (content of memory) in the future. Positive meaning finding, but not focusing on neutral or negative aspects of a memory, led to the subsequent re-emergence of positive emotion and positive memory content 1-week later (Experiment 3). Critically, we replicated this finding across 4 additional experiments. Adaptive updates were long-lasting, remaining even after 2-months, highlighting the durability and longevity of the effect (Experiment 4). Positive meaning finding only led to updates after a reminder and a 24h, but not 1h delay, consistent with a reconsolidation account (Experiment 5). It was also more effective than receiving a monetary reward after retrieval (Experiment 6). Using multi-session fMRI, positively reinterpreted memories had greater neural pattern dissimilarity at future retrieval in regions associated with memory (hippocampus) and reward (striatum), suggesting a greater change in the neural representation of memory (Experiment 7). Together, this research highlights how savoring positive emotions is adaptive for coping with negative affective states, which has implications for adaptive psychological wellbeing and protection from clinical disorders.

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Chapter 1: Introduction

1.1 General Introduction

Whether we are sitting in traffic, receiving bad news from a friend, or worrying about our health, we can all benefit from successfully regulating our emotions. Clinicians and researchers have made great strides in examining cognitive strategies that can rescue us from our fears, anxiety, and sadness (Ochsner & Gross, 2005), which has tremendous value given that a central feature of clinical disorders is negative affect (Baumeister, Bratslavsky, Finkenauer, & Vohs, 2001). However, the ability to flexibly generate or savor *positive emotions* when feeling down or to boost already pleasant feelings that enhance the current experience is also adaptive for wellbeing (Quoidbach, Berry, Hansenne, & Mikolajczak, 2010). Understanding the efficacy of positive emotion-focused strategies and interventions could therefore help explain why under similar circumstances some people flourish while others feel depressed (Catalino & Fredrickson, 2011).

Research on positive emotion regulation is growing rapidly. One reason is that positive emotions have adaptive value. That is, positive emotions help us learn what is rewarding in our environment, thus promoting appetitive goal-directed behavior (Haber & Knutson, 2010). According to the broaden-and-build theory, cultivating positive emotions can build psychological resources leading to enhanced coping and resilience to future adversity, by broadening one's scope of cognition (Fredrickson, Danner, & Snowdon, 2003; Tugade & Fredrickson, 2004). This is especially important considering that some strategies aimed at diminishing negative emotions are somewhat ineffective under stress (Raio, Orederu, Palazzolo, Shurick, & Phelps, 2013). Despite the demonstrated effectiveness of common regulation strategies (e.g., reappraisal) in daily life (Gross &

John, 2003), people do not actually choose to use them as often as one might think (Suri, Whittaker, & Gross, 2014), suggesting the critical need for identifying the behavioral and neural bases of strategies aimed at savoring positive emotions.

The overarching goal of this dissertation is to examine the important question of whether positive emotion-focused regulation strategies can effectively mitigate negative affective states. This dissertation begins by discussing the current challenges in regulating our emotions under stressful and aversive circumstances, and then highlights the behavioral and neural components of alternative forms of coping via savoring positive emotions (e.g., positive reminiscence and positive meaning finding) that may be more efficacious for dealing with negative affective states. Following this, it outlines seven experiments utilizing behavioral, acute stress, neuroendocrine, and neuroimaging methods. The aim of the first two experiments is to test the influence of savoring positive emotions via memory retrieval on acute stress exposure (Chapter 2). The last five experiments explore how finding positive meaning in past negative memories impacts our emotions, transforms our memory, and how this is represented in the brain (Chapters 3 & 4).

1.2 Emotion Regulation during Negative Affective States

1.2.1 Cognitive emotion regulation

In our everyday lives, we encounter challenges and setbacks that can evoke unwanted feelings. Sometimes it is possible to change our external situation to regulate these feelings (e.g., avoiding a grumpy neighbor). When this is not possible, we must change our internal responses instead. Humans employ various cognitive strategies to regulate our emotional state (Brans, Koval, Verduyn, Lim, & Kuppens, 2013). For instance,

we might try to dampen aversive feelings altogether, known as suppression, or we could limit our attentional resources to an emotionally aversive stimulus in favor of something less problematic, known as distraction (Ochsner & Gross, 2005). However, the regulatory strategy most widely studied is cognitive change, specifically cognitive reappraisal (Buhle et al., 2014; Webb, Miles, & Sheeran, 2012).

Cognitive reappraisal involves altering the way we think about an emotional stimulus to change how we feel about it (Gross, 2002). In an experimental setting, individuals are typically asked to re-interpret a stimulus (e.g., images, film clips, words) to reduce its emotional impact, such as reframing the meaning of a situation or our emotional response to it. For instance, anxious arousal before public speaking could be reframed as feelings of excitement. Countless studies have shown this strategy to be highly efficacious in reducing negative emotion via subjective self-report (e.g., Ray, McRae, Ochsner, & Gross, 2010; for review see Webb et al., 2012). There is also evidence that cognitive reappraisal can diminish physiological arousal, although the findings have been mixed (Hofmann, Heering, Sawyer, & Asnaani, 2009; Kim & Hamann, 2012).

1.2.2 Neural circuitry of emotion regulation

An emerging literature has begun to explore the neural mechanisms underlying cognitive emotion regulation. Negative affect is most commonly associated with increased activity in the amygdala—a subcortical region linked to emotion processing, particularly for fear, negative affect, and salient stimuli (LeDoux, 2014). Observations from neuroimaging studies show a reduction in amygdala activity when down-regulating negative emotion using cognitive reappraisal, along with increases in lateral prefrontal

(PFC) regions linked to cognitive control and response inhibition, such as the dorsolateral (DLPFC) and ventrolateral (VLPFC) prefrontal cortex (e.g., Goldin, McRae, Ramel, & Gross, 2008; Kanske, Heissler, Schönfelder, Bongers, & Wessa, 2011; Ochsner et al., 2004). Although there are no direct connections between the amygdala and DLPFC, there is evidence to suggest that other prefrontal regions mediate this effect such as the ventromedial prefrontal cortex (VMPFC) or VLPFC (Ochsner, Silvers, & Buhle, 2012; Wager, Davidson, Hughes, Lindquist, & Ochsner, 2008). A recent study further demonstrated that the strength of DLPFC–VLPFC/inferior frontal gyrus connectivity was associated with cognitive reappraisal success (Morawetz, Bode, Baudewig, Kirilina, & Heekeren, 2016).

1.2.3 Coping with acute stress

Stress is ubiquitous throughout our lives and often occurs unexpectedly. It elicits negative emotions, has detrimental effects on our psychological and physical well-being (Lazarus & Folkman, 1984), and is also a precursor to anxiety and depressive episodes (Kendler, Karkowski, & Prescott, 1999), making it imperative to identify effective strategies for reducing stress.

Perceiving a threat or stressor in the environment triggers a response in two biological systems in the body. The faster-acting response in the sympathetic nervous system releases catecholamines from the adrenal medulla, which increases heart rate and physiological arousal to prepare the body for action (the ‘fight or flight’ response) (McEwen, 2007). The slower-acting response occurs in the hypothalamic-pituitary-adrenal (HPA) axis, which has a longer lasting impact on emotion and cognition. After a stressor,

the HPA-axis coordinates the release of glucocorticoids from the adrenal cortex. This includes the primary neuroendocrine marker of stress, cortisol, which takes about 15 min to rise (Kirschbaum & Hellhammer, 1994; Lupien, Maheu, Tu, Fiocco, & Schramek, 2007). Although lower levels of stress can be beneficial to performance in some contexts, elevated cortisol due to acute or chronic stress is linked to a host of detrimental effects on our affective and cognitive functioning. For instance, acute stress has been associated with impaired learning, decision-making (Porcelli & Delgado, 2009, 2017), and working memory (Schoofs, Wolf, & Smeets, 2009)—processes all requiring prefrontal cortex involvement. Unsurprisingly, stress also impacts our mood, by eliciting negative emotions and inhibiting the reward system in the brain (Pizzagalli, Bogdan, Ratner, & Jahn, 2007; Porcelli, Lewis, & Delgado, 2012).

While we can successfully employ various cognitive strategies to cope with unwanted feelings in daily life, it is no secret that regulating our emotions is more challenging under stress. Indeed, previous research has shown that stress can hinder our ability to utilize common regulation strategies, such as reappraisal—an integral component of cognitive behavioral therapy (Beck, 2011). In the absence of stress, participants can successfully diminish conditioned fear responses (e.g., reduced skin conductance responses—a measure of physiological arousal), but participants fail to do so under stress (Raio et al., 2013). Not only are some strategies less successful under stress, but individuals widely vary with respect to the strategies they choose to use (Sheppes et al., 2014) and are able to use for coping (Folkman, Lazarus, Gruen, & DeLongis, 1986; Shallcross, Troy, & Mauss, 2015; Troy, Shallcross, & Mauss, 2013), underscoring the need for alternative strategies for regulating our response to acute stressors.

1.2.4 Coping with negative autobiographical memories

The retrieval of autobiographical memories that evoke personal episodic information in one's life can bring back emotions tied to the original experience (Westermann, Spies, Stahl, & Hesse, 1996). Autobiographical memories have adaptive functions in that they can bolster a sense of self-identity (Bluck, Alea, Habermas, & Rubin, 2005), help shape the future (Schacter & Addis, 2007) and influence an individual's well-being (Young, Bellgowan, Bodurka, & Drevets, 2013).

However, some memories can also have maladaptive consequences, for instance, when the content leads to perseverating on negative thoughts and promoting anxiety. Such is the case of negative memories characterized by high arousal and self-relevance or high personal involvement—factors that contribute to the retention of memories (Holland & Kensinger, 2010) and can be triggered by cues in the environment associated with the negative event (Lyubomirsky, Caldwell, & Nolen-Hoeksema, 1998). The recall of negative autobiographical memories can exacerbate symptoms related to various clinical disorders, including depression (Young, Siegle, Bodurka, & Drevets, 2015) and post-traumatic stress disorder (Moore & Zoellner, 2007; Rubin, Boals, & Berntsen, 2008). It is thought that failures of emotion regulation (Gotlib & Joormann, 2010), which can lead to increases in neural responses in regions such as the amygdala (Young, Drevets, Bodurka, & Preskorn, 2016) and overgeneralization of autobiographical memories and rumination (Hamlat et al., 2015), may underlie these maladaptive consequences associated with negative autobiographical memory recall. Thus, understanding how negative memories can be regulated and updated is of critical importance.

1.3 Positive Emotion-focused Coping

Given the evidence described thus far, alleviating stress and negative emotions triggered by past negative events is challenging. While we can utilize common emotion regulation strategies that aim to dampen negative feelings in daily life, they are not always effective for everyone (e.g., depressed individuals; Troy et al., 2013) or in every context (e.g., stress; Raio et al., 2013), suggesting the need for alternative forms of coping. One potential alternative is to focus on enhancing or savoring positive emotions instead.

1.3.1 Savoring positive emotions enhances wellbeing

Savoring is the process of intentionally attending to positive information in an appreciative way (Bryant & Veroff, 2007). The goal of savoring can be to sustain, enhance, or prolong a positive experience or emotion. Importantly, a greater propensity for savoring in daily life is linked to better physical health (Nelson & Cooper, 2005), greater happiness (Quoidbach et al., 2010), and fewer depressive symptoms and psychological distress (Seligman, Steen, Park, & Peterson, 2005).

We can savor our positive emotional experience in various ways. For instance, we can approach a situation with optimism or humor (Sharot, Riccardi, Raio, & Phelps, 2007; Wu et al., 2013), use guided imagery (imagine a peaceful waterfall or quiet beach; e.g., Fredrickson, Mancuso, Branigan, & Tugade, 2000), be present-focused (practicing mindful awareness; e.g., Bishop et al., 2004), engage in mental time travel (reminiscing about the past or daydreaming about the future; e.g., Speer, Bhanji, & Delgado, 2014), or celebrate and share positive experiences with others (Lambert et al., 2012; Quoidbach, Wood, & Hansenne, 2009). Such strategies not only bolster positive feelings in response to positive

stimuli (Gross, 1998) but they also lead to increased behavioral displays of happiness (e.g., smiling) and elevated physiological measures (i.e., heart rate, blood pressure, skin conductance; Giuliani, McRae, & Gross, 2008). Internally generating positive emotions in response to positive stimuli consistently recruits reward-related regions, such as the ventral striatum (VS) and orbitofrontal cortex (OFC) (Kim & Hamann, 2007), as well as the prefrontal cortex, particularly the DLPFC and MPFC (Habel, Klein, Kellermann, Shah, & Schneider, 2005).

1.3.2 Reminiscing about positive autobiographical memories

A powerful way to bolster positive emotions is to use mental time travel. Our capacity to mentally travel back in time affords us the opportunity to re-live happy moments over and over again. That is, reminiscing about pleasant memories can bring back positive feelings associated with the original experience (e.g., Bower, 1981; Westermann, Spies, Stahl, & Hesse, 1996), such as remembering the birth of a child. Observations from neuroimaging studies show that positive emotion evoked by reminiscing about pleasant memories engages regions previously implicated in reward processing, such as the striatum, VMPFC, and OFC (e.g., Cerqueira et al., 2008; Lempert, Speer, Delgado, & Phelps, 2017; Markowitsch, Vandekerckhove, Lanfermann, & Russ, 2003; Speer et al., 2014), regions associated with cognitive control, such as the medial PFC, lateral PFC, and dorsal anterior cingulate cortex (dACC) (Ochsner et al., 2012), and regions associated with memory processing and retrieval, such as the lateral and medial parietal cortex and medial temporal lobe including the hippocampus (Addis, Wong, & Schacter, 2007; Bechara, Damasio, & Damasio, 2000; Svoboda, McKinnon, & Levine, 2006).

Positive memories not only rekindle pleasant feelings but are also thought to be intrinsically valuable to an individual (Speer et al., 2014). For instance, individuals were willing to forgo money for the opportunity to reminisce about them. Greater striatal signal during positive reminiscence was also correlated with individual measures of resiliency, and led to mood improvement in some individuals, demonstrating the potential value in reminiscing about our own happy memories as an emotion regulation strategy.

Given these findings, can positive memory retrieval be used as an emotion regulation strategy following stress or other negative affective states? Recalling the positive past is something we already do naturally, and thus may be less effortful than other forms of regulation (that is, for individuals who have no difficulty in recalling the positive past). It is also a proactive form of savoring and does not require a cue or need for reinterpretation, and therefore could presumably be implemented at any time. Whether reminiscing about positive memories can be used as a way to alleviate a stressful experience or even to prolong or savor an already pleasant experience is yet to be explored. This is the focus of Aim 1 (see Chapter 2 for Experiments 1 and 2).

1.3.3 Finding positive meaning in negative autobiographical memories

Another positive emotion-focused strategy is positive meaning finding, which is also termed benefit finding, positive reappraisal, or posttraumatic growth (Folkman, 2008; Thompson, 1985). Positive meaning finding is a form of reactive savoring whereby individuals re-evaluate a stressful or negative experience in a more positive light. Importantly, individuals who can find positive meaning in stressful life events, such as a serious health issue or the death of a loved one, report better health behaviors and greater

psychological wellbeing overall (Mokowitz, Folkman, Collette, & Vittinghoff, 1996). Such individuals also have greater trait resilience—the ability to bounce back quickly from adversity—which is further mediated by the experience of positive emotion (Tugade & Fredrickson, 2004).

Although positive meaning finding is a form of reinterpretation or reappraisal, it is distinctly different from more traditional reappraisal strategies that ask individuals to focus on minimizing negative affect (i.e., minimizing reappraisal) or distancing themselves from a negative situation (i.e., distancing). Only a handful of studies have explicitly compared reappraisal strategies that enhance positive feelings to those that reduce negative feelings. A clever analogy to distinguish them, as described by Shiota & Levinson (2012), is when listening to a bad song on the radio, one option is to turn down the volume (i.e., minimizing reappraisal). But a better strategy might be to simply change the channel (i.e., positive reappraisal), which equally achieves our goal of eliminating the bad song while also providing a positive outcome: we still get to listen to good music. Empirically, both strategies reduce negative affect and individuals report similar success rates when using them (Dore et al., 2016; McRae, Ciesielski, & Gross, 2012; Shiota & Levenson, 2012). However, positive meaning finding is uniquely linked to increased positive emotion, and in some cases a greater reduction in negative emotion than minimizing (Dore et al., 2016; McRae, Ciesielski, et al., 2012; Shiota & Levenson, 2012). It also leads to more positive thoughts when re-evaluating negative stimuli, with content indicating greater humor or amusement, perceiving distressing social relationships as being closer or stronger (Shiota & Levenson, 2012), and generating more positive words and fewer negative words as compared to minimizing (Dore et al., 2016).

Observations of physiology reveal unique signatures for these two strategies as well. Reappraisal via decreasing negative emotions leads to a greater reduction in skin conductance responses than increasing positive emotions (McRae, Ciesielski, et al., 2012), suggesting that minimizing strategies may reduce negative valence and arousal, whereas positive coping strategies may only reduce valence. One interpretation is that perhaps positive coping strategies preserve arousal in order to adaptively prime the individual for taking positive action in response to a stressor, whereas negative emotion-focused strategies simply dampen our emotional response to diminish the stressor's impact. Consistent with this notion, cardiovascular response profiles suggest that positive reappraisal may lead to a 'challenge mindset' (reduced blood pressure and shorter cardiac inter-beat interval) rather than a 'threat mindset' (Shiota & Levenson, 2012).

The neural systems supporting increases in positive emotion vs. decreasing negative emotions reflect these distinct patterns in emotion and physiology. Finding positive meaning in negative contexts engages reward-related neural circuits such as the ventral striatum (VS) and VMPFC (Dore et al., 2016). Notably, minimizing reappraisal led to reduced amygdala activity, whereas positive meaning finding led to stronger positive connectivity between the VMPFC and amygdala, consistent with physiological evidence that positive emotion-focused coping may preserve arousal in anticipation of future action. These results mirror prior work that identified two different neural pathways mediating prefrontal activity (VLPFC) and reappraisal success (Wager et al., 2008). Although this study did not assess specific reappraisal strategy use or goals, one pathway was mediated by reductions in amygdala activity, which may reflect decreasing negativity or minimizing,

whereas the other pathway was mediated by increased VS activity (particularly the nucleus accumbens; NAcc), which may reflect increasing positivity.

Although no neuroimaging studies to our knowledge have examined positive meaning finding in the context of one's past negative memories, there is some behavioral evidence that positive emotion-focused coping strategies can counter negative affect evoked by a variety of stimuli. For example, positive emotion induction manipulations, such as thinking about amusing things, can have a positive impact on cardiovascular functioning following reminders of fearful events (Fredrickson & Levenson, 1998). Positive strategies, such as focusing on being grateful, have been suggested to induce a positive reframing (Wood, Joseph, & Linley, 2007). Using this strategy when writing about an aversive memory (as opposed to the more traditional disclosure technique; e.g., Pennebaker, Mayne, & Fracis, 1997), resulted in a feeling of "closure" on the memory and less unpleasant emotional responses to it. This suggests that positive emotion-focused strategies, such as positive meaning finding, could be an effective way of coping with negative affect associated with autobiographical memories. This is the focus of Aim 2 and 3 (see Chapter 3 and 4 for Experiments 3-7).

1.4 Interaction between Emotion and Memory Systems

1.4.1 Overlap in neural circuitry of memory and emotion regulation

There is some notable overlap between the neural circuitry of emotion regulation and the recall of autobiographical memories. Similar to the emotion regulation literature described previously, retrieving autobiographical memories relies on a particular neural circuitry that includes distinct regions of the lateral and medial prefrontal cortex (Holland

& Kensinger, 2010), along with the amygdala in relation to vividness and arousal (Sharot, Martorella, Delgado, & Phelps, 2007) and the hippocampus for more recent memories (Cabeza & St Jacques, 2007).

This presents the opportunity to ask whether emotion regulation can be used as a way to cope with the deleterious effects of recalling negative memories. Indeed, a few researchers have examined if negative autobiographical memories can be regulated by strategies such as minimizing reappraisal or distancing. The common observation includes dampening of the intensity experienced after recalling these memories and recruitment of lateral PFC regions (Holland & Kensinger, 2013; Kross, Davidson, Weber, & Ochsner, 2009). Interestingly, a failure in regulating such memories is associated with increased amygdala activity and rumination (Young et al., 2015) and is associated with disorders such as depression (Gotlib & Joormann, 2010).

While these negative memory regulation studies are consistent with prior emotion regulation literature using other negative stimuli—successful regulation leads to cortical control over regions such as the amygdala—they are also limited by a few factors. First, given that memory was only probed once in these studies, it is unclear if the effects of regulation provide long-term beneficial effects. That is, can regulation and associated neural circuitry have long lasting effects in future retrieval of autobiographical memories? Second, cognitive regulation strategies such as reappraisal are not always effective and can be compromised when individuals are under stress (Raio et al., 2013), potentially because cortical mechanisms and its functional connections essential for regulation tend to be impacted by neuromodulatory changes occurring under stress (Arnsten, 2009). This opens the door for testing the behavioral and neural correlates of alternative strategies, such as

positive emotion-focused coping, given that identifying and reengaging in positive activities can enhance well-being (Mazzucchelli, Kane, & Rees, 2010).

Taken together, understanding whether and how the neural circuitries of positive emotion regulation and memory processing interact could help explain the potential mechanisms by which reframing negative memories in a positive light contributes to enhanced wellbeing.

1.4.2 The influence of emotion on memory formation, storage and retrieval

Although the experiments in this dissertation focus on memory retrieval, it is important to first consider how memories come to be, which critically relies on emotion. From the time of encoding, emotions bias our attention toward events of emotion significance, which ultimately shapes what reaches our awareness (Anderson, 2005) and eventually gets stored in our memory—through a process called consolidation. During consolidation, information slowly assimilates into storage to eventually form stable memory traces (McGaugh, 2000). Given this slow process, memories are fragile and can be modified during consolidation. In this way, important events eliciting greater physiological arousal may be more significant for survival, and therefore benefit from stronger consolidation that increases their likelihood of being remembered in the future. Memory traces for less important events are likely to weaken and be later forgotten.

Seminal evidence supporting the idea of consolidation showed that memory in rodents is impaired if disruptions (e.g., shock or protein synthesis inhibitors) occur during the consolidation window (i.e., shortly after encoding), whereas memory is preserved if disruptions occur after longer delays (Duncan, 1949; Flexner, Flexner, & Stellar, 1965).

Similarly, in humans, arousing words are better remembered relative to neutral words after a longer delay (1h to 1-day) rather than a shorter one (immediate) (Kleinsmith & Kaplan, 1963; LaBar & Phelps, 1998). Emotional arousal is thought to adaptively influence memory consolidation via the release of stress hormones (epinephrine and glucocorticoids) from the adrenal gland in response to the emotional event itself (McGaugh, 2000). Stress hormones then activate the amygdala (McGaugh & Roozendaal, 2002), which in turn has a modulatory role in enhancing consolidation in the hippocampus—a primary neural region for memory processing and storage located adjacent to the amygdala in the medial temporal lobe. Consistent with animal models, damage to the amygdala in humans or administration of drugs that block stress hormones (e.g., β-adrenergic receptor antagonists) results in diminished memory for emotionally arousing information, while preserving memory for neutral information (Cahill, Prins, Weber, & McGaugh, 1994), whereas eliciting stress hormone responses via pain or pharmacological modulation immediately after encoding leads to enhanced memory (Cahill & Alkire, 2003; Cahill, Gorski, & Le, 2003).

Emotional memory enhancement has been well documented across the literature in studies using a range of emotional stimuli (words, stories, pictures, and film clips; for review see Hamann, 2001). Emotion does not only boost memory. It can also have a powerful influence on our subjective sense of remembering, especially when remembering real-life personal events termed autobiographical memories. For some memories, we might vividly recall people, places, and events with a high level of detail. For other memories, we might only recognize that we have seen something before without recalling the context, such as recognizing a familiar face but not being able to place where the person was met or how one knows them (Yonelinas, 2002).

One simple way memory researchers study how emotion affects our subjective sense of remembering is by asking participants to make remember (Do you vividly remember this?) versus know judgments (Do you recognize this?). What they have found is that memory tends to be greater for emotional stimuli than neutral stimuli when individuals state they vividly remember seeing the stimuli rather than simply recognizing they saw it (i.e., know) (Dewhurst & Parry, 2000; Kensinger & Corkin, 2003; Ochsner, 2000). This is true even when recall rates are similar for emotional and nonemotional information (Ochsner, 2000; Sharot, Delgado, & Phelps, 2004), suggesting that individuals not only have a general memory boost for emotional versus neutral events but that they re-experience emotional events more vividly. Neuroimaging evidence suggests that a heightened sense of remembering has distinct neural signatures for emotional versus neutral stimuli (Sharot et al., 2004). That is, vividly remembering an emotionally negative photo or significant event engages the amygdala (Sharot, Martorella, et al., 2007), which has been linked to emotional arousal and perceptual fluency, whereas remembering a neutral photo engages the posterior parahippocampus, which is associated with successful memory retrieval (Slotnick & Schacter, 2004) and recognition of perceptual details (Cabeza, Rao, Wagner, Mayer, & Schacter, 2001).

Other researchers extended these findings by demonstrating that emotion might be influencing vividness at retrieval by enhancing the amount of detail remembered. Specifically, participants performed better for emotional material than neutral material on tasks where they were asked to distinguish between previously seen images and similar images that were never seen before (e.g., same verbal label or category; Kensinger, Garoff-Eaton, & Schacter, 2006). When performing other types of categorization tasks, such as

distinguishing between previously seen objects versus objects that had only been imagined (Kensinger & Schacter, 2005) or distinguishing between stimuli in an emotional context versus neutral context (Smith, Stephan, Rugg, & Dolan, 2006), correct attributions for emotional information were associated with greater activity in the amygdala, hippocampus, and orbitofrontal cortex, suggesting a role for these regions in aiding the remembrance of emotional events with enhanced detail.

In summary, emotion affects what reaches our awareness, ultimately shaping what is stored and later can be remembered for future survival (for review, see Kensinger & Kark, 2017). This is accomplished through the critical involvement of MTL regions, such as the amygdala and hippocampus, and their reciprocal interactions with each other and with other brain regions (e.g., visual processing stream).

1.4.3 Memory modification and updating

Autobiographical memory recollection is a reconstructive process (Tulving, 2002). As described in the prior section, after encoding, memory is thought to be fragile until consolidation into a stabilized memory trace. Well-consolidated memories can then return to a fragile state (i.e., destabilization), where they are prone to modification, once reactivated during retrieval. Such memories undergo a second consolidation to restabilize and persist, called reconsolidation (Lewis, 1979; Nader & Einarsson, 2010; Nader & Hardt, 2009; Nader, Schafe, & Le Doux, 2000). This is a potential mechanism through which we can update old memories with new content.

Initial evidence for reconsolidation came from a study in rodents, demonstrating that conditioned fear memories could be disrupted by impairing the amygdala, but only if

impairment occurred during the reconsolidation window (i.e., shortly after reactivation, but not after 6h; Nader, Schafe, & Le Doux, 2000). In humans, reactivated fear memories can be updated with non-fearful stimuli (via extinction) during the reconsolidation window, preventing the return of fear at later retrieval (+24h), evidenced by reduced physiological arousal (Schiller et al., 2010) and dampened amygdala activity (Agren et al., 2012). Across humans and animals, memory updating via reconsolidation has now been shown for a variety of experimental paradigms, including fear conditioning (Schiller et al., 2010), motor memory (Walker, Brakefield, Hobson, & Stickgold, 2003), spatial memory (Jones, Bukoski, Nadel, & Fellous, 2012), and episodic memory (Hupbach, Gomez, Hardt, & Nadel, 2007), and using a myriad of interventions, such as new learning (Hupbach et al., 2007), extinction (Schiller et al., 2010), counterconditioning (Goltseker, Bolotin, & Barak, 2017), and distraction via playing tetris (James et al., 2015).

What researchers have learned from this body of work is that the following conditions must be met for memory updating via reconsolidation to occur. First, the memory must be accessed and 'reactivated' prior to modification, in order for destabilization to result (Hardwicke, Taqi, & Shanks, 2016; Nader & Hardt, 2009). This is often accomplished through retrieval, but not always (Hardwicke et al., 2016; Sevenster, Beckers, & Kindt, 2012). Second, the memory interference (or modifying intervention) must occur during the reconsolidation window (i.e., shortly after and up to ~6h later), but not after a delay (~6h or more). Third, the interference or manipulation should create a prediction error—or mismatch between what is expected and what actually occurs—in order for the memory to destabilize (Krawczyk, Fernández, Pedreira, & Boccia, 2017; Sevenster, Beckers, & Kindt, 2014). Fourth, changes to the memory must be observable

only after a delay (often measured 24h later), but not shortly after modification. That is, there should be no evidence of changes to the memory during the reconsolidation window (lasting up to 6h after reactivation), given that it takes time for restabilization of the memory.

It is important to note that after reconsolidation the original memory is not erased, but rather updated and incorporating new content. If the requirements of reconsolidation are not satisfied, yet changes to the memory are still observed, this would suggest that a new memory has been formed that potentially competes with the original, rather than an update to the original (or in addition to an update to the original, if evidence of reconsolidation is also present).

The discovery that a stored memory does not remain in a fixed state and is prone to modification at future retrieval has important clinical implications. However, since only a handful of studies have examined memory updating and reconsolidation processes, little is known about the mechanisms by which these memory processes work, especially in the brain, or how current findings extend to autobiographical memories that are ubiquitous in everyday life. Exploring the propensity for maladaptive memories to be updated with positive content has translational potential for informing new treatments for individuals with mood disorders or post-traumatic stress disorder (PTSD) who not only have difficulty regulating emotion, but may also face difficulty in successfully reshaping negative memories into more positive ones (Schwabe, Nader, & Pruessner, 2014).

1.5 General Description and Significance of Dissertation Experiments

The literature reviewed in the preceding sections outlines the behavioral and neural components of positive emotion-focused regulation strategies and their potential benefits to one's wellbeing, in terms of influencing mood, dampening stress, and modifying maladaptive memories. While it is conceivable that savoring positive emotions could counteract negative affective states, researchers have primarily focused on cognitive regulation strategies aimed at dampening negative emotions, leaving unclear the efficacy of positive emotion-focused coping strategies. This dissertation seeks to address these gaps in the literature through 3 Aims (7 Experiments):

Aim 1. The ability to dampen negative feelings via reappraisal in response to negative stimuli is ineffective under stress (Raio et al., 2013). A potential alternative is to utilize positive emotion-focused strategies that enhance positive feelings instead. One such strategy—positive memory reminiscence—has been shown to engage corticostriatal circuits that track positivity and self-reported resiliency (Speer et al., 2014), thus making it a promising strategy for potentially dampening responses to acute stress. Given that acute stress elicits negative emotion, lessens our ability to use cognitive emotion regulation, and diminishes responsiveness to rewards, it is of critical importance to identify effective strategies for reducing stress. Experiment 1 (Speer & Delgado, 2017) investigated whether savoring positive emotions (via memory recall) could diminish the physiological and emotional consequences of stress exposure. Participants underwent an acute stressor or control task followed by autobiographical memory recollection (of only positive or neutral valence). We hypothesized that positive reminiscence, but not neutral reminiscence, would result in dampened stress hormone levels (e.g., cortisol) and reduced negative affect.

Experiment 2 extends the findings of Experiment 1 to examine the neural mechanisms underlying the stress buffering effects of positive memory recall using fMRI. Previous research shows that cognitive control regions engaged during emotion regulation (DLPFC, VLPFC) are typically impaired under stress (Arnsten, 2009). Understanding how the brain responds to stress and the neural circuitry associated with overcoming stress via positive emotion can inform future treatments for anxiety and mood-related disorders. Experiment 2 (Speer & Delgado, 2017) utilized the same experimental paradigm as Experiment 1, except it occurred during fMRI scanning. Our first goal was to replicate the behavioral and physiological findings from Experiment 1 (i.e., improve mood and dampen cortisol response). Our second hypothesis was that reminiscing about positive memories would recruit regions previously associated with positive emotion during memory recall (e.g., striatum; Speer et al., 2014) and emotion regulation processes (Morawetz, Bode, Derntl, & Heekeren, 2017) to overcome the detrimental consequences of acute stress. Our third hypothesis was that positive reminiscence would be associated with greater connectivity in emotion regulatory regions (VLPFC, DLPFC) that correlated with positivity—as measured via psychophysiological interaction analysis (PPI).

Aim 2. Finding positive meaning in past negative events is central to therapeutic techniques and is associated with enhanced mental health outcomes (Gross & John, 2003). However, it remains unclear whether positive meaning finding during memory retrieval actually changes the memory representation itself. Memory is reconstructed at the time of retrieval (Tulving, 2002), leaving the potential for modification each time the memory is reopened, and allowing for new information to update the old through a reconsolidation process (Lee, Nader, & Schiller, 2017; Nader & Einarsson, 2010). Experiment 3 sought to

investigate whether reinterpreting negative memories in a more positive light leads to the updating and subsequent re-emergence of positivity at future retrieval. Participants first reactivated negative autobiographical memories via writing a description of them and making emotion ratings. Afterwards, they elaborated on them by either focusing on the positive aspects (Positive group), negative aspects (Negative group), or neutral aspects (Neutral group) of each memory or performed a distracting perception task (Distraction group). To test for changes over time, they wrote about and rated their memories again 1-week later. We hypothesized that only the Positive group would show enhanced positive emotion at future retrieval. We also predicted that individuals in the Positive group who had the greatest increase in positive feelings would also show the greatest change in positive content across retrieval sessions, indicating that negative memories had been successfully updated with positive content.

As a next step, Experiment 4 used the same paradigm as Experiment 3, but with these additional goals: a) we compared positive meaning finding (Positive group) to a control condition in which individuals naturally recalled their memories without attempting to modify them (Control group), b) we examined changes in emotion and written memory content across time within a larger sample of individuals who used positive meaning finding, and c) we examined the longevity of memory change by adding a 3rd session occurring 2-months later. Thus, Experiment 4 served as both a replication and longitudinal extension of Experiment 3. We predicted that the Positive group would show a greater increase in positive emotion and greater change in memory content (in terms of positive language use/tone and dissimilarity in details of the events) compared to the Control group after both 1-week and 2-months.

Experiment 5 builds on Experiments 3-4 to explicitly test the mechanism by which positive meaning finding updates negative memories with positive content. To test whether a memory has been updated via reconsolidation: a) the memory must first be accessed and 'opened up' prior to modification, b) memory modification must occur during the reconsolidation window (i.e., shortly after and up to ~6h later) and c) there must be evidence of changes to the memory 24h after modification but not before (e.g., not during the ~6h reconsolidation window). Thus, Experiment 5 examined if successful updating of negative memories using positive meaning finding occurs via reconsolidation. Three groups of participants first recalled negative memories via mental recall as a means of reactivation. Afterwards they were asked to positively elaborate on half of them (positive condition), and only naturally recall the other half (as a control condition). Two groups (Delayed-test, Immediate-test) reactivated the memories prior to the positive manipulation, whereas one group (No-reminder) did not. To examine memory change at future retrieval, all groups returned to mentally recall and emotionally rate their memories again. Importantly, two groups (Delayed-test, No-reminder) returned 24h later (after reconsolidation window), whereas one group (Immediate-test) returned 1h later (during the reconsolidation window). We hypothesized that only the Delayed-test group (who underwent reactivation prior to the positive manipulation and were tested after a 24h delay) would show enhanced positive emotion at future retrieval for positively reinterpreted memories, but not control memories. The two other groups (Immediate-test—tested at 1h delay; No-reminder—no reactivation prior to positive manipulation) would show no such changes. This would provide sufficient evidence that successfully updating negative memories using positive meaning finding occurs through a reconsolidation process.

Experiment 6 extended this work to test whether another strategy that enhances positive emotion—receiving an extrinsic monetary reward after retrieval—would similarly update memory with positive content, much like positive meaning finding. We employed a paradigm mirroring the Delayed-test group from Experiment 5, comparing two positive manipulations in a between-subject design: the Positive group used positive meaning finding whereas the Money group received a monetary reward after retrieval. Each group also used natural recollection as a comparison control condition. Our hypothesis was that only positive meaning finding (Positive group) would show enhanced positive emotion at future retrieval, but not receiving a monetary reward (Money group), suggesting that the intrinsic meaning of the positive strategy might matter for updating negative memories via positivity.

Aim 3. Prior neuroimaging research shows that dampening negative emotion using cognitive strategies modulates prefrontal-limbic circuitry (amygdala, lateral PFC; Buhle et al., 2014), whereas enhancing positive emotion during memory recall increases reward-related neural activity (MPFC, striatum; Speer et al., 2014). How might the synergistic interaction of positive emotion regulatory and memory circuitries in the brain lead to positive changes in maladaptive memories via positive meaning finding? Building on the behavioral evidence from Experiments 3-6, Experiment 7 investigated how updating negative memories with positive content changes the neural representation of memories at future retrieval. This was a multi-session fMRI scanning study. During fMRI scan #1, participants reactivated their negative memories via mental recall and made emotion ratings. Immediately after, they did an Elaboration task where they positively reinterpreted half of them (positive condition), and naturally recalled the other half (control condition).

To test for changes over time, they returned 24h later to mentally recall and emotionally rate their memories again during fMRI scan #2.

Beyond replicating our behavioral findings from Experiments 3-6, we had three key neural hypotheses. First, we predicted that positive elaboration relative to natural recall (tracking the degree of feeling change) will elicit greater activity in emotion regulatory and reward-related regions (PFC, striatum) during the elaboration task and also after updating (Recall 2). Second, we used Representational Similarity Analysis (RSA) to test similarity in patterns of neural activity across retrieval sessions (Visser, Kunze, Westhoff, Scholte, & Kindt, 2015). Our hypothesis was that positively reinterpreted memories will be less similar across retrievals than control memories, providing evidence that positive meaning finding leads to greater changes in the neural representation of memories. Third, we predicted that greater changes in feeling (for positively elaborated memories) and individual protective traits (savoring ability, resilience) would be associated with a) greater emotion regulatory and/or reward-related activity during elaboration and b) greater neural dissimilarity across retrievals.

Taken together, this dissertation seeks to examine whether positive emotion-focused coping strategies can regulate negative affect elicited by experiencing acute stress (via positive reminiscence) and stemming from remembering negative memories from the past (via finding positive meaning in them). This research can shed light on the neural circuitry underpinning positive emotion regulation and its interactions with autobiographical memory retrieval. In turn, this may inspire translational research to inform clinical treatments for individuals with anxiety, depression, and stress-related disorders.

Chapter 2: Reminiscing about Positive Memories buffers Acute Stress Responses [Experiments 1 & 2]

2.1 Introduction

Acute stress can leave us feeling anxious and distressed, with detrimental consequences to our physical and mental health (Lazarus & Folkman, 1984). We often use cognitive regulation strategies to suppress these unpleasant feelings altogether (e.g., suppression) or to reinterpret the negative situation into something less negative or neutral (e.g., cognitive reappraisal; Gross, 2002). Despite our best efforts, however, we are not always successful in diminishing unpleasant feelings when using cognitive strategies under stress (Raio et al., 2013). This may not be surprising considering that stress is thought to compromise the exact neural circuitry that emotion regulation relies on (Arnsten, 2009). Thus, a promising alternative may be to focus on increasing or sustaining positive feelings—a strategy that broadens one's cognitive perspective (Catalino & Fredrickson, 2011)—and may foster better coping with the stressor.

One way of bolstering positive emotions is to reminisce about past positive events. Indeed, autobiographical memories can bring back emotions tied to the original experience (Bower, 1981). Retrieving positive memories in particular may be intrinsically valuable, by re-kindling pleasant feelings and engaging neural circuitry involved in reward-processing (e.g., striatum; Speer et al., 2014). Notably, such striatal activity correlates with self-reported resiliency and enhanced mood for some individuals, consistent with a role for corticostriatal circuits in sustaining positive mood (Admon & Pizzagalli, 2015; Heller et

al., 2009). Thus, savoring happy memories might be significant for one's ability to cope with stress, potentially promoting better decision-making and wellbeing.

Yet, a critical question remains whether recalling the positive past can actually facilitate successful adaptation to stress (i.e., resiliency). Experiencing stress activates the hypothalamic-pituitary-adrenal (HPA) axis, which releases a cascade of hormones including the primary stress hormone cortisol (Kirschbaum & Hellhammer, 1994). Heightened cortisol response after stress has deleterious effects on affective and cognitive states, disrupting processes supported by the prefrontal cortex such as working memory (Schoofs et al., 2009) and decision-making (Porcelli & Delgado, 2009, 2017). Acute stress is also thought to be a precursor to depressive episodes (Kendler et al., 1999) and may influence reward systems (Porcelli et al., 2012). Individuals widely vary with respect to the psychological resources they have and the strategies they implement for coping with acute stressors (Folkman et al., 1986). Cognitive regulation strategies (e.g., reappraisal) that are typically effective for diminishing negative affect elicited by images (Buhle et al., 2014) or conditioned stimuli (Delgado, Nearing, Ledoux, & Phelps, 2008) are often rendered ineffective after stress exposure (Raio et al., 2013), highlighting a need for alternative ways to combat stress. The present study investigates one potential mechanism: remembering the good times. That is, can simply reminiscing about our own positive memories help diminish the physiological (e.g., reduce cortisol) and emotional consequences of stress exposure? Further, what are the neural mechanisms underlying the ability to buffer the effects of stress by recalling the positive past?

We explored this idea first behaviorally (N=134) and then using functional Magnetic Resonance Imaging (fMRI; N=43). In the behavioral study (Experiment 1), we

exposed participants to an acute stressor or control task prior to autobiographical memory recollection. Importantly, half of the sample reminisced about positive memories, whereas the other half reminisced about neutral memories, creating four experimental groups: *Stress-Positive* (N=33), *Stress-Neutral* (N=34), *Control-Positive* (N=33), and *Control-Neutral* (N=34; see Fig 2.1 for timeline). Stress participants underwent the Socially Evaluative Cold Pressor task (SECPT; immersed hand in ice cold water under social threat; Schwabe, Haddad, & Schachinger, 2008), which reliably activates the HPA axis, producing elevated cortisol levels about 15 min after the stressor (Kirschbaum & Hellhammer, 1994). To assess physiological changes to stress over time, salivary cortisol was collected at baseline (*s*1), after memory recollection when cortisol was expected to peak (*s*2, +20 min), and at the conclusion of the experiment when cortisol was expected to recover (*s*3, +50 min). We hypothesized that recalling positive memories, relative to neutral memories, would buffer the negative effects of stress by a) decreasing the cortisol response and b) having a positive effect on mood.

We then investigated the neural correlates underlying the stress buffering effects of positive autobiographical memory retrieval. The fMRI study (Experiment 2) was nearly identical in terms of design to the behavioral study (see Methods), with the goal of comparing two groups exposed to stress that undergo different memory treatments (*Stress-Positive*=22; *Stress-Neutral*=21). We hypothesized that reminiscing about the positive past would recruit regions previously associated with positive emotion during memory recall (e.g., striatum; Speer et al., 2014) and emotion regulation processes (Morawetz et al., 2017) to overcome the detrimental consequences of acute stress.

2.2 Experiment 1: Methods

2.2.1 Participants

Healthy undergraduate students (N=149) at Rutgers University completed Day 1 and returned for Day 2 only if they met inclusion criteria (see Day 1 procedures; 139 met criteria). Additional exclusions included not following directions (<50% responses; N=2) and extreme cortisol responses (>3 SD from mean; N=3). Participants from the final sample (N=134; 44 males; M_{age}= 20.8, SD= 4.2) were randomly assigned to four experimental groups: *Stress-Neutral* (N=34), *Control-Neutral* (N=34), *Stress-Positive* (N=33), and *Control-Positive* (N=33). We chose thirty-five participants per group as our target sample size to attain an effect size comparable to prior stress studies, which typically have a between-subjects design with 30-35 participants per group (e.g., Raio et al., 2013). Participants gave informed consent in accordance with the Rutgers University Institutional Review Board for the Protection of Human Subjects in Research and received course credit for their participation.

2.2.2 Experimental Design

Day 1: Autobiographical memory questionnaire. Participants were presented with 84 common life event cues (e.g., Family Vacation). For each cue, participants selected a real memory in which they had been personally involved and had occurred at a specific place and time. Participants then reported a description, location, date, and gave subjective ratings for valence (positive or neutral), emotional intensity (i.e., how intense was the memory; 1-4: 1= not intense, 4= very intense), and feeling (i.e., how did you feel when you recalled this memory; 1-4: 1= neither good nor bad, 4= very good). Importantly,

memories were positive (e.g. visiting Disneyland) or neutral (e.g. packing for a trip), but not negative memories (e.g., lost luggage).

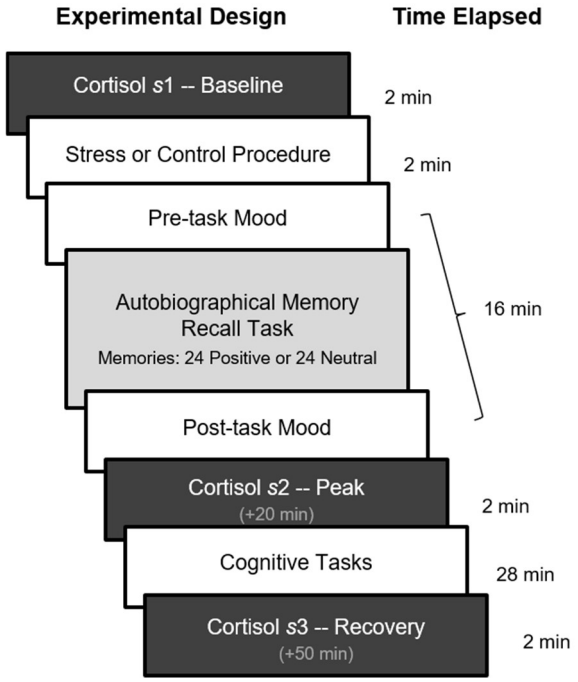


Figure 2.1. Schematic of Experimental Procedure and Timeline of Neuroendocrine Assessments for Day 2 (Stress Manipulation or Control Task). Salivary samples were collected immediately before the stress or control procedure (*s*1, baseline), after memory recollection when cortisol was expected to peak (*s*2, peak, +20 min), and at the conclusion of the experiment when cortisol was expected to recover (*s*3, recovery, +50 min).

Only participants who reported at least 24 positive or 24 neutral memories (depending on random assignment) returned for Day 2. For each participant, the 24 most positive (or neutral) cues were used in the memory recall task on Day 2. Participants also completed the Connor-Davidson Resiliency scale (Connor & Davidson, 2003) and the Beck Depression Inventory (Beck, Ward, Mendelson, Mock, & Erbaugh, 1961).

Day 2: Stress induction and memory recall. The second session (three days later) was run between 1:00pm and 5:30pm to account for diurnal variations in cortisol levels (Kirschbaum & Hellhammer, 1994). Participants were informed of the stress procedure and notified that they could withdraw from the experiment at any time. Day 2 included: 1) salivary cortisol collection *s*1, 2) stress induction or control procedure, 3) pre-task mood assessment, 4) cued recall autobiographical memory task of either only positive memories or of only neutral

memories, 5) post-task mood assessment, 6) salivary cortisol collection *s*2, 7) cognitive tasks, 8) salivary cortisol collection *s*3 (Fig 2.1).

2.2.3 Stress Induction

We used the Socially Evaluative Cold Pressor task (SECPT; Schwabe et al., 2008) for induction of acute stress. Stress participants were videotaped while immersing their hand into ice water (1-3°C) for 2 min. The experimenter dressed in a white lab coat recorded the participant and acted neutral. Participants were told that the recording would be used for further analysis after the session. The control task was identical except that participants immersed their hand in warm water (23-25°C), there was no video camera, and no lab coat. Afterwards, participants rated how unpleasant, stressful, and painful it was ranging from 0 (not at all) to 100 (very much). The sum of these three ratings created a subjective stress rating.

2.2.4 Neuroendocrine Measurement and Analysis

Salivary samples were collected to assess cortisol concentrations, via swab placed under the tongue for 2 min. Swabs were kept in cold storage at -10°C until sent to Salimetrics Laboratory for duplicate biochemical assay analysis. To assess cortisol change across time, we calculated the area under the curve with respect to increases from baseline (AUC_I) for each participant using the trapezoidal method.

To assess sympathetic nervous system arousal, we measured skin conductance via electrodes placed on the participant's fingers, sampled at 200 Hz using an MP100 Data Acquisition Module (Biopac Systems). During the 2 min SECPT/control procedure, skin

conductance levels (SCL) were measured as the mean tonic activity. During the memory task, skin conductance responses (SCR) were assessed via the sum of trough-to-peak waveform amplitude responses (in microsiemens, μS) across all trials (0.5s to 14.5s window; square-root transformed). Responses lower than 0.02 μS were recorded as zero. Data were preprocessed by low-pass filtering (25 Hz cut-off) and mean-value smoothing using a three-sample window.

2.2.5 Autobiographical Recall Task

Participants first reported their current mood state via the PANAS (Watson, Clark, & Tellegen, 1988). Then, they completed a cued recall autobiographical memory task where they reminisced about 24 positive memories (Positive groups) or 24 neutral memories (Neutral groups) triggered by event cues from their Day 1 questionnaire. Each trial included one written event cue displayed for 14s. Participants recalled the same memory from Day 1 and elaborated on it until the 14s were up. Participants made button presses to indicate the ‘‘beginning’’ (i.e., when it began to form) and ‘‘end’’ of their memory (if they finished elaborating before time was up). After a delay of 2–4s, participants rated the memory for emotional intensity and feeling (3.5s each). The length of one trial was 24 sec, with a delay of 6-10s separating one trial from the next. Afterwards, participants rated their post-recall mood state via the PANAS. We did not assess mood before the stressor, because we assumed baseline mood levels would be similar across groups given random assignment.

2.2.6 Behavioral Analysis

Group differences in subjective stress ratings, SCL/SCR, AUC_I cortisol response, autobiographical memory task performance, and mood were tested using Condition (stress/control) by Valence (positive/neutral) ANOVAs. We included demographic variables as covariates in our analyses such as age, depressive symptoms (BDI), resiliency (CD-RISC), gender, and menstrual cycle phase (collected for 64 out of 90 female participants; luteal phase= 40; follicular phase= 24). None of these factors significantly impacted the results.

2.3 Experiment 1: Results

2.3.1 Autobiographical Memory Recollection

During the cued autobiographical memory recall task, 134 healthy adults (44 males; age= 20.8, SD= 4.2) reminisced about 24 real memories from their past prompted by common life event cues (e.g., Family Vacation; Speer et al., 2014). Event cues were selected to be either positive (e.g., Visiting Disneyland) or neutral in valence (e.g., Packing for a trip), depending on random group assignment, and were validated in a session three days prior. On each trial, participants had 14 sec to reminisce about the chosen memory and made button presses to indicate the onset and duration of recollection. For each memory, they gave subjective emotion ratings in terms of feeling (i.e., how did you feel when you recalled this memory) and emotional intensity (i.e., how intense was the particular memory).

As expected, individuals who reminisced about positive memories experienced greater positive feeling ($F_{1,130}$= 422.08, $p < .001$) and emotional intensity ($F_{1,130}$= 202.39,

p< .001) than individuals who reminisced about neutral memories, regardless of stress or control condition. Although individuals who recalled positive memories rated their memories as being higher in emotional intensity based on subjective ratings, there were no differences in skin conductance responses (SCRs) across the groups (all p> .32), suggesting that individuals had similar levels of sympathetic nervous system arousal during recollection, and group differences cannot merely be explained by arousal. There were also no differences in memory onset (all p> .17) or recall duration (all p> .31) across groups, indicating that neither the memory valence nor the condition (stress, control) influenced difficulty in recall.

2.3.2 Recalling the Positive Past Dampens Cortisol Response after Stress Exposure

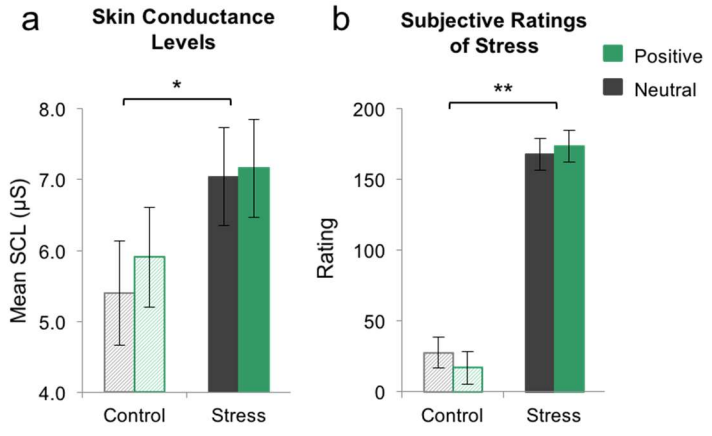


Figure 2.2. Physiological and Subjective Responses to Acute Stress in the Behavioral Study. a) Individuals exposed to acute stress had larger mean SCL during the SECPT/control procedure and b) greater subjective ratings of stress after the SECPT/control procedure than control participants. *p < .05; **p < .001; error bars denote SEM.

We first confirmed that our stress manipulation (SECPT; Schwabe et al., 2008) was effective in inducing acute stress. In accordance, stressed participants had greater skin conductance levels (SCL) during the SECPT (t_{125}= 2.06, p= .042), which is an indicator of sympathetic nervous system arousal, and reported greater subjective ratings of stress afterwards (t_{132}= 13.70, p< .001) than control participants (Fig 2.2).

We next observed changes in cortisol over time between stress and control conditions (Fig 2.3a; individual data points are reported for better visualization of the data). Specifically, we calculated the area under the curve with respect to increases from baseline (AUC_I) for each participant using the trapezoidal method. We selected AUC_I as our measure because it takes into account both time-related changes and overall intensity of the cortisol response (Pruessner, Kirschbaum, Meinlschmid, & Hellhammer, 2003). A Condition (Stress/Control) by Valence (Positive/Neutral) ANOVA examining AUC_I revealed a main effect of Condition ($F_{1,130}$= 5.74, p= .018), confirming that the stress procedure elevated cortisol levels whereas the control procedure did not (M_{Stress}= 0.76, SD= 5.65; $M_{Control}$= -1.30, SD= 4.40), a main effect of Valence ($F_{1,130}$= 7.66, p= .006), indicating dampened cortisol levels for positive relative to neutral recall regardless of condition ($M_{Positive}$= -1.47, SD= 0.61 $M_{Neutral}$= 0.90, SD= 0.60), and a non-significant interaction ($F_{1,130}$= 0.26, p= .609).

We then tested for group differences in AUC_I to examine our specific hypothesis that recalling positive memories, but not neutral memories, would dampen the typical rise in cortisol after stress exposure. This analysis was necessary to confirm that our main effect of valence for AUC_I was not simply driven by differences between *Control-Positive* and *Control-Neutral* groups. In line with our prediction, AUC_I for the *Stress-Positive* group was significantly smaller than the *Stress-Neutral* group ($M_{Stress\text{-}Positive}$= -0.67, SD= 4.70; $M_{Stress\text{-}Neutral}$= 2.14, SD= 6.20; t_{65}= -2.09, p= .041, d= 0.52, 95% confidence interval {0.1196 to 5.5004}; Fig 2.3b). This is particularly interesting when considering that before memory recollection the *Stress-Positive* group reported high subjective stress levels and had elevated SCLs just like the *Stress-Neutral* group (both p> .81), yet these individuals

still exhibited lower cortisol levels after memory recollection. This suggests that internally generated positive emotion evoked by autobiographical recall may help dampen the heightened physiological response to acute stress.

2.3.3 Recalling the Positive Past Influences Mood after Stress Exposure

Given that individuals in the *Stress-Positive* group showed a dampened cortisol response, a critical question we sought to answer was whether recalling positive memories would also have a positive effect on mood, despite stress exposure. We assessed mood before and after memory recollection using the PANAS (Watson et al., 1988).

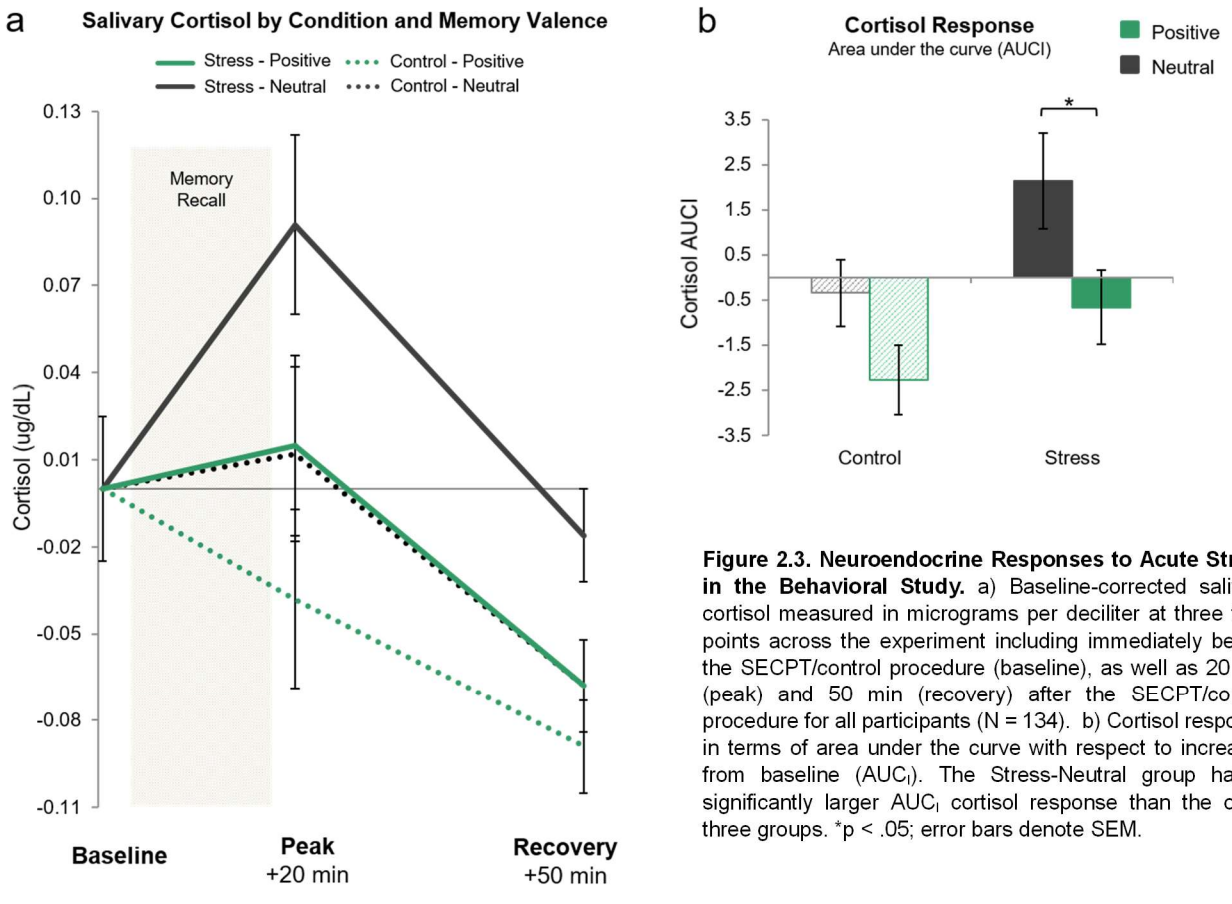


Figure 2.3. Neuroendocrine Responses to Acute Stress in the Behavioral Study. a) Baseline-corrected salivary cortisol measured in micrograms per deciliter at three time points across the experiment including immediately before the SECPT/control procedure (baseline), as well as 20 min (peak) and 50 min (recovery) after the SECPT/control procedure for all participants (N = 134). b) Cortisol response in terms of area under the curve with respect to increases from baseline (AUC_I). The Stress-Neutral group has a significantly larger AUC_I cortisol response than the other three groups. *p < .05; error bars denote SEM.

For negative affect, we observed a significant Valence (positive/neutral) by Condition (stress/control) interaction for post-recall negative affect ($F_{1,130}$= 5.53, p= .04). The *Stress-Positive* group reported lower negative affect after memory recollection than the *Stress-Neutral* group ($M_{Stress\text{-}Positive}$= 14.48; SD= 4.12; $M_{Stress\text{-}Neutral}$= 17.06; SD= 6.88; t_{65}= -1.68, p= .069), which was trending but did not reach statistical significance.

Although there were no significant group differences for positive affect, we observed individual differences within the *Stress-Positive* group such that generating greater positive feelings during recollection was associated with enhanced mood (r_{32}= 0.34, p= .05). In our prior study (Speer et al., 2014), the strength of striatal activation while recalling positive memories was positively correlated with self-reported resiliency. This motivated the idea that resilient individuals who have greater adaptation to stress might be better able to utilize positive memories to increase positive feelings during recollection, in turn making them more successful in boosting their overall mood, even under stress. We explored the possibility that resiliency mediates the relation between positive emotion generated during recollection and enhanced mood after recollection using a mediation model (Fig 2.4).

For *Stress-Positive* individuals, greater self-reported resiliency was associated with both greater positive emotion during memory recollection (Fig 2.4a) and with enhanced positive mood afterwards (Fig 2.4b). To test whether self-reported resiliency was a mediator in this relationship, we conducted a bootstrapping analysis based on 5,000 bootstrapped samples (Preacher & Hayes, 2004). The total effect of emotion during recall on mood after recall was significant (path c: B= 6.53, SE= 3.28, t_{32}= 2.00, p= .05), but this relation was no longer significant when controlling for resiliency (direct effect, path c': B=

2.76, SE= 3.41, t_{32}= 0.81, p= .42: Fig 2.4c). Further, the indirect effect of emotion during recall (through resiliency) on subsequent mood was significant, indicating full mediation (B= 3.73, SE= 2.34, bias corrected bootstrapping 95% confidence interval {0.04 to 8.98}). An important consideration is that baseline positive emotion did not differ between high and low resiliency individuals ($M_{High\text{-}res}$= 30.4, SD= 7.43; $M_{Low\text{-}res}$= 27.6, SD= 5.89; t_{20}= 1.22, p= .233) and thus does not account for the finding. In sum, our results demonstrate that, for Stress-Positive individuals, positive emotion during memory recall related to greater resilience, which in turn related to better mood.

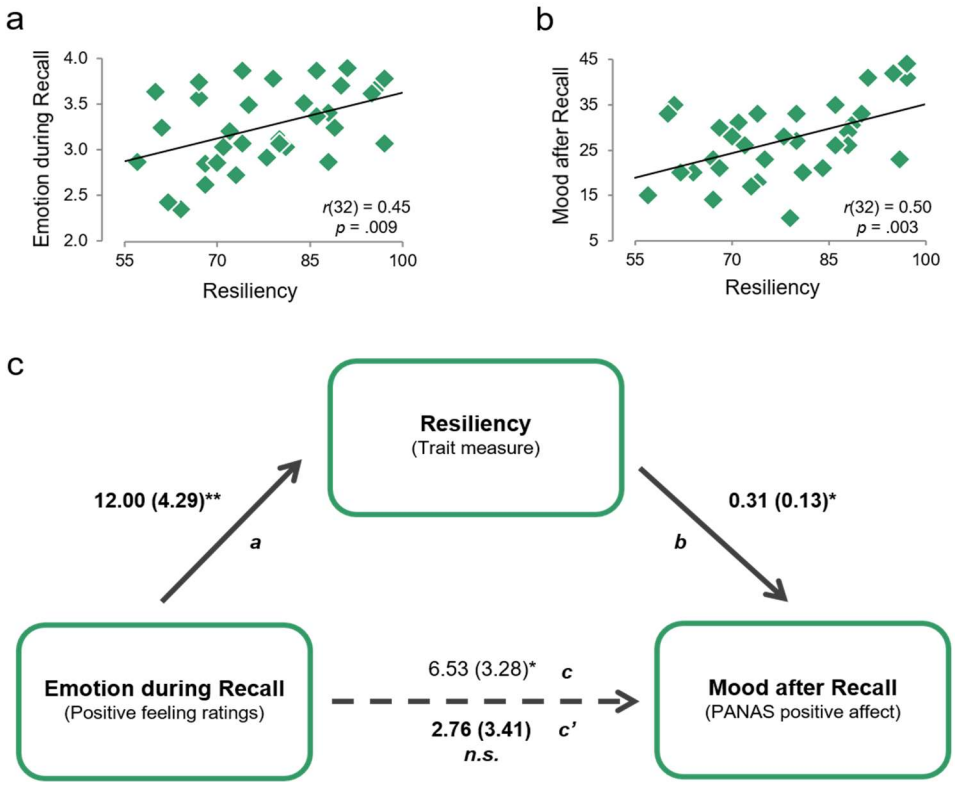


Figure 2.4. Resiliency Mediates the Relationship between Emotion Ratings during Memory Recall and Subsequent Mood for Individuals in the Stress-Positive Group. a) Greater resiliency (measured by the CD-RISC scale; N = 33) is associated with greater positive feelings during positive memory recollection. b) Greater resiliency is also associated with enhanced mood after positive memory recollection. c) Mediational model between emotion during recall, self-reported resiliency, and mood after recall. Path a: effect of emotion during recall on resiliency; path b: effect of resiliency on mood after recall, controlling for emotion during recall; path c: total effect of emotion during recall on mood after recall; and path c': direct effect of emotion during recall on mood after recall, controlling for resilience. Path values represent unstandardized regression coefficients. *p < .05; **p < .01

2.4 Examining the neural circuitry of the stress-buffering effects of positive reminiscence

Our behavioral findings highlight the restorative nature of positive autobiographical memory recollection under stress. We demonstrated that reminiscing about positive memories—but not neutral memories—led to a dampened rise in cortisol and lower levels of negative affect, instead of the heightened response characteristic of stress. As a next step, we sought to identify the neural mechanisms through which stress-buffering via positive memory recollection occurs. Given that recalling happy memories increases positive feelings and striatal activity (Speer et al., 2014) and may serve emotion regulatory functions as per our behavioral study, we hypothesized such mechanisms to include corticostriatal systems involved in positive mood (Admon & Pizzagalli, 2015) and emotion regulation (Wager et al., 2008). We conducted an fMRI study that mirrored our behavioral design focused on the *Stress-Positive* and *Stress-Neutral* groups.

2.5 Experiment 2: Methods

2.5.1 Participants

Fifty-two healthy adults participated. Exclusions included not following directions (<50% responses, N=1), extreme cortisol responses (N=7), and claustrophobia (N=1). Participants from the final sample (N=43) were randomly assigned to two experimental groups: *Stress-Positive* (N=22, 9 males, age= 22.4, SD= 3.3) or *Stress-Neutral* (N=21, 10 males, age= 23.4, SD= 5.2). Participants gave informed consent in accordance with the Rutgers University Institutional Review Board for the Protection of Human Subjects in Research and received compensation for their participation.

2.5.2 Experimental Design

Day 1: Autobiographical memory questionnaire. This session was identical to the behavioral study.

Day 2: Stress induction and fMRI scanning. Participants returned for the second session two to four days later. Day 2 included: 1) salivary cortisol collection *s*1 (baseline), 2) stress induction via the SECPT in the scanning environment, 3) salivary cortisol collection *s*2, 4) Set-up in the scanner, 5) pre-task mood assessment, 6) cued recall autobiographical memory task of either only positive memories or of only neutral memories, 7) post-task mood assessment, 8) salivary cortisol collection *s*3 (+24 min, peak), 9) reward task, 10) salivary cortisol collection *s*4 (+58 min, recovery; Fig 2.5).

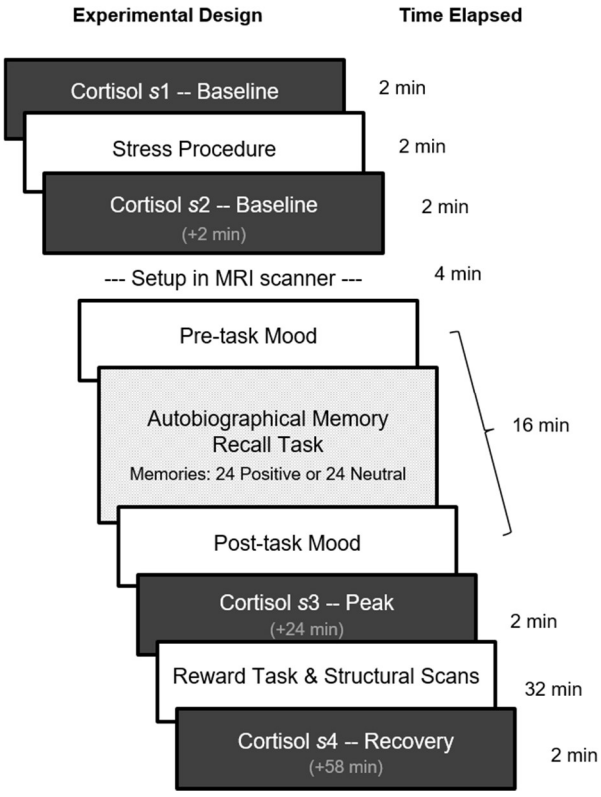


Figure 2.5. Schematic of Experimental Procedure and Timeline of Neuroendocrine Assessments for Day 2 (Stress Manipulation) for the fMRI study. Salivary samples were collected immediately before the stress procedure (*s*1, baseline), immediately after the stress procedure (*s*2, +2 min), after memory recollection when cortisol was expected to peak (*s*3, peak, +24 min), and at the conclusion of the experiment when cortisol was expected to recover (*s*4, recovery, +58 min).

We used the same memory recall task as described previously for the behavioral design (24 positive or 24 neutral memories depending on group assignment). Cortisol collection and SECPT administration were identical to the behavioral study with minor changes to be compatible with the fMRI scanner environment. For instance, all cortisol samples were collected while the participant was in the scanner room. To allow for the participant to acclimate to the

scanner environment and for salivary cortisol to stabilize, the baseline sample (*s*1) was collected 30 min after the participant arrived and 10 min after being in the scanner room. The peak cortisol response (*s*3) was the only sample collected while the participant was in the scanner because it occurred between runs of the memory task and the reward task. While the fMRI design had an additional cortisol sample (as described above), which was included in this analysis, it is important to note that this sample did not differ from the baseline cortisol measurement (taken 2 min earlier; p= .525) given the slow nature of cortisol release after stress exposure (10-15 min) (Kirschbaum & Hellhammer, 1994). For our stress protocol (SECPT), participants immersed their hand in ice cold water (1-3°C) for 2 min, while sitting in the scanner room. The experimenter dressed in a white lab coat videotaped the participant from the doorway. Consistent with the behavioral study, we collected SCR during the SECPT and subjective stress ratings after.

We also asked participants to perform a surprise monetary reward task (the card-guessing game adapted from (Delgado, Nystrom, Fissell, Noll, & Fiez, 2000)) while still in the scanner. This task was a surprise as to not influence the prior memory task and mood ratings. The purpose was to identify reward-related regions of interest (ROIs) to serve as independent ROIs to test with high and low feeling memory regressors across groups. In each trial of the card task, participants saw a card with a question mark inside for 2s. They guessed whether the card's value was higher or lower than the number 5 via button press. After a 2-4s delay, the card and monetary outcome were displayed for 2s. A correct response earned a green checkmark signifying a gain of $1.00 whereas an incorrect response earned a red X signifying a loss of $0.50. Unbeknownst to participants, outcomes were predetermined to control schedule of reinforcement and number of gain and loss trials

(20 each for a total of 40 trials). A trial lasted 9s, with a delay of 4-6s separating one trial from the next.

At the conclusion of the scanning session, participants were debriefed and compensated for their time in the scanner and bonus money earned in the card game.

2.5.3 fMRI Data Acquisition

A 3T Siemens Magnetom Trio scanner was used for acquisition of T2-weighted MPRAGE structural images (256 x 256 matrix, FOV= 256 mm, 176 1-mm sagittal slices). Functional images were taken in 35 contiguous oblique-axial slices (3x3x3 mm voxels) prescribed parallel to the AC-PC plane with a single shot gradient echo EPI sequence (TR= 2s, TE= 25ms, FOV= 192, flip angle 90, bandwidth= 2232 Hz/Px, echo spacing= 0.51). Data were preprocessed and analyzed using BrainVoyager QX (v2.8, Brain Innovation). Functional images were motion-corrected (six parameters), slice-timing corrected using a cubic spline interpolation, and spatially smoothed using a Gaussian kernel of 4mm FWHM. Further, the data were temporally smoothed with voxelwise linear detrending and high-pass filtering of frequencies (three cycles per time course). The images were spatially normalized to the Talairach stereotaxic space (Talairach & Tournoux, 1988).

2.5.4 fMRI Data Analysis

Functional data were analyzed using a whole brain random-effects general linear model (GLM). The memory task was modeled using a regressor for memory recall, a parametric regressor for subjective feeling ratings during memory recall (orthogonalized with respect to the memory regressor), and a regressor representing missed trials (i.e., no

valence rating given for the memory, 1.6% missed trials). The memory regressor and feeling parametric regressor began at memory formation and ended after elaboration, with this period defined by participants' own button presses in each trial (for onset and conclusion of memory recall). We performed three analyses. We first examined the parametric modulation of feeling in each group separately, and then a contrast of *Stress-Positive* > *Stress-Neutral* to examine group differences in neural activity as a function of subjective feeling ratings during memory recollection. This allowed us to test for regions whose activity increased linearly as feeling ratings increased on a trial-by-trial basis for each of these analyses.

The monetary reward task was modeled using two regressors representing gain and loss trials during the 2s outcome phase along with a regressor representing missed trials (no response). We conducted a contrast of gain and loss outcomes to identify reward-related ROIs. Using the functionally defined reward ROIs in the striatum, we then ran a GLM using high (rating of 3 or 4) and low (rating of 1 or 2) feeling memory regressors. The goal of this analysis was to confirm that a "reward-related" functionally defined ROI would show an independent effect of high versus low feeling during memory recall for the *Stress-Positive* relative to the *Stress-Neutral* group.

For both the memory and monetary reward tasks, regressors were convolved with a canonical double-gamma hemodynamic response function and six regressors for motion parameters were included in the model. To correct for multiple comparisons, we used the cluster level statistical threshold plugin in Brain Voyager (Goebel, Esposito, & Formisano, 2006). This plugin employs Monte Carlo simulations to determine the likelihood that observed clusters of activation are significant and not false positives (over 1000 iterations),

resulting in a whole brain corrected threshold of $p < .01$. After correction, the map automatically applies the minimum cluster size threshold that produces the desired cluster-level false-positive alpha rate (1% was chosen). For the memory task, we applied a voxel cluster threshold of 8 contiguous voxels ($216mm^3$ as determined by the plugin) defined at a threshold of $p < .001$ to obtain a corrected alpha $< .01$. Because our goal for the monetary reward task was to simply identify independent ROIs, we applied a more stringent initial threshold of $p < .000001$ (which required a voxel cluster threshold of 1 voxel, $27mm^3$, to obtain a corrected alpha $< .01$).

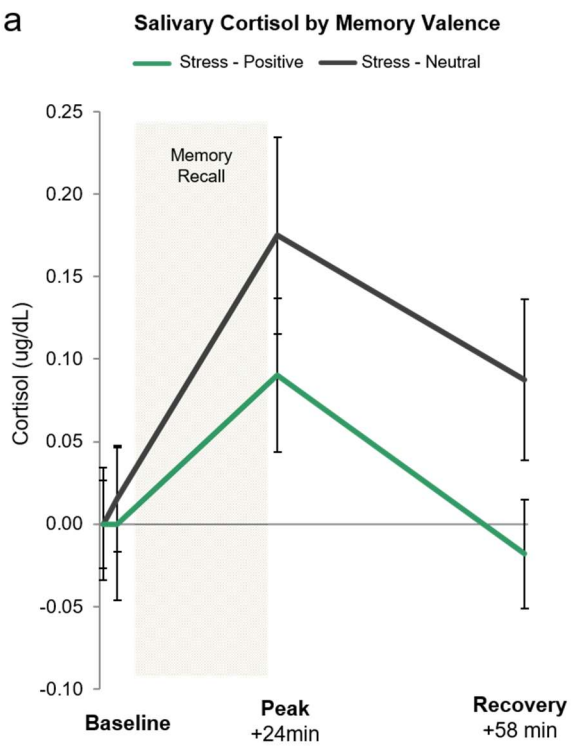
2.5.5. Psychophysiological Interaction Analysis

To identify neural regions that were functionally connected to cortical regions identified in our main contrast of memory recall as a function of subject feeling ratings during positive memory recollection, we conducted an exploratory psychophysiological interaction (PPI) analysis. We chose our prefrontal cortex seed regions based on our parametric modulation of feeling during memory recollection (e.g., right and left VLPFC). The regressor of interest—the PPI interaction term—was created by calculating the element-by-element product of the seed region time series (physiological factor) and trial-by-trial subjective feeling ratings (psychological factor) during the memory recollection task. Each PPI model included regressors for the interaction term (psychophysiological factor), the time series of the seed region (physiological factor), and trial-by-trial subjective feeling ratings (psychological factor). For each subject, we extracted volumes of interest to use as seeds in single-subject whole-brain PPI analyses. These were then combined into a group level model for performing a random-effects whole brain analysis to identify

regions exhibiting connectivity with the seed region. To correct for multiple comparisons, we set an initial threshold of $p < .001$ and applied a cluster correction of 8 contiguous voxels ($216mm^3$) to obtain a corrected alpha< .01.

2.6 Experiment 2: Results

We asked a new cohort of participants (N=43) to undergo an acute stress procedure (SECPT) before fMRI scanning. Afterwards, they reminisced about only 24 positive memories (N=22, 9 males, age= 22.4, SD= 3.3) or only 24 neutral memories (N=21, 10 males, age= 23.4, SD= 5.2) while undergoing fMRI scanning. Performance on the autobiographical memory task matched the behavioral sample. That is, the *Stress-Positive* group reported greater positive feeling ($M_{Stress\text{-}Positive}$= 2.90, SD= 0.33; $M_{Stress\text{-}Neutral}$= 2.06, SD= 0.52; t_{41}= 6.41, p< .001) and emotional intensity ($M_{Stress\text{-}Positive}$= 2.42, SD= 0.41;



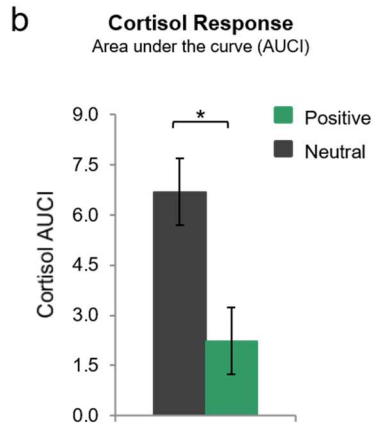


Figure 2.6. Neuroendocrine Responses to Acute Stress in the fMRI Study. a) Baseline-corrected salivary cortisol measured in micrograms per deciliter at four time points including immediately before the SECPT/control procedure (baseline), as well as 2 min, 24 min (peak) and 58 min (recovery) after the SECPT/control procedure for all participants (N = 43). b) Cortisol response in terms of area under the curve with respect to increases from baseline (AUC_I). Stress-Neutral group has a significantly larger AUC_I cortisol response than the Stress-Positive group. *p < .05; error bars denote SEM.

$M_{Stress\text{-}Neutral}$= 1.76, SD= 0.47; t_{41}= 4.89, p< .001) than the *Stress-Neutral* group, with no differences in memory onset or recall duration between groups (both p> .68).

Of particular significance, our cortisol results in the fMRI study replicated the behavioral study. Specifically, individuals who recalled positive memories had a smaller AUC_I cortisol response than individuals who recalled neutral memories ($M_{Stress\text{-}Positive}$= 2.23, SD= 6.25; $M_{Stress\text{-}Neutral}$= 6.69, SD= 7.10; t_{41}= -2.19, p= .035, d= 0.68, 95% confidence interval {0.3454 to 8.5746}; Fig 2.6a and b). Consistent with the behavioral study, this occurred even though the two stress groups did not differ in subjective ratings of stress or SCLs during the stress procedure (both p> .37). In the context of mood, *Stress-Positive* individuals reported less negative affect after memory recall than *Stress-Neutral* individuals ($M_{Stress\text{-}Positive}$= 11.91; SD= 2.11; $M_{Stress\text{-}Neutral}$= 14.90; SD= 6.01; t_{41}= -2.20, p= .033).

2.6.1 Reminiscing about positive memories to combat stress recruits regions associated with emotion regulation

To examine the neural mechanisms associated with the dampening of the stress response via positive memory recollection, we conducted a random-effects whole-brain general linear model (GLM) that focused on the time of memory recall for *Stress-Positive* individuals. Importantly, because we hypothesized that enhancing positive emotion may be critical for reducing the stress response, we included trial-by-trial feeling ratings as a parametric modulator of memory recollection. We tested for regions whose activity increased linearly as feeling ratings increased, resulting in a statistical map set to an initial threshold of p< .001 (as suggested by Eklund, Nichols, & Knutsson, 2016) and corrected

to a whole-brain cluster correction of p< .01 (using 216 mm^3 as determined by BrainVoyager's cluster-level threshold plugin (Goebel et al., 2006)).

This parametric regression analysis of feeling identified regions being modulated by increases in subjective feeling ratings during memory recall for *Stress-Positive* individuals (Fig 2.7a, Table 2.1). Notably, these included prefrontal regions previously implicated in cognitive control and emotion regulation such as bilateral ventrolateral prefrontal cortex (Buhle et al., 2014) and corticostriatal regions associated with reward-processing, such as the right ventral striatum and medial prefrontal cortex (Delgado, 2007; O'Doherty, 2012). The same analysis in the *Stress-Neutral* group yielded no significant clusters. As a complementary analysis, we also examined feelings as a parametric modulator during memory recall contrasting the *Stress-Positive* relative to the *Stress-Neutral* groups, which revealed the right VLPFC (same peak coordinates as prior analysis)

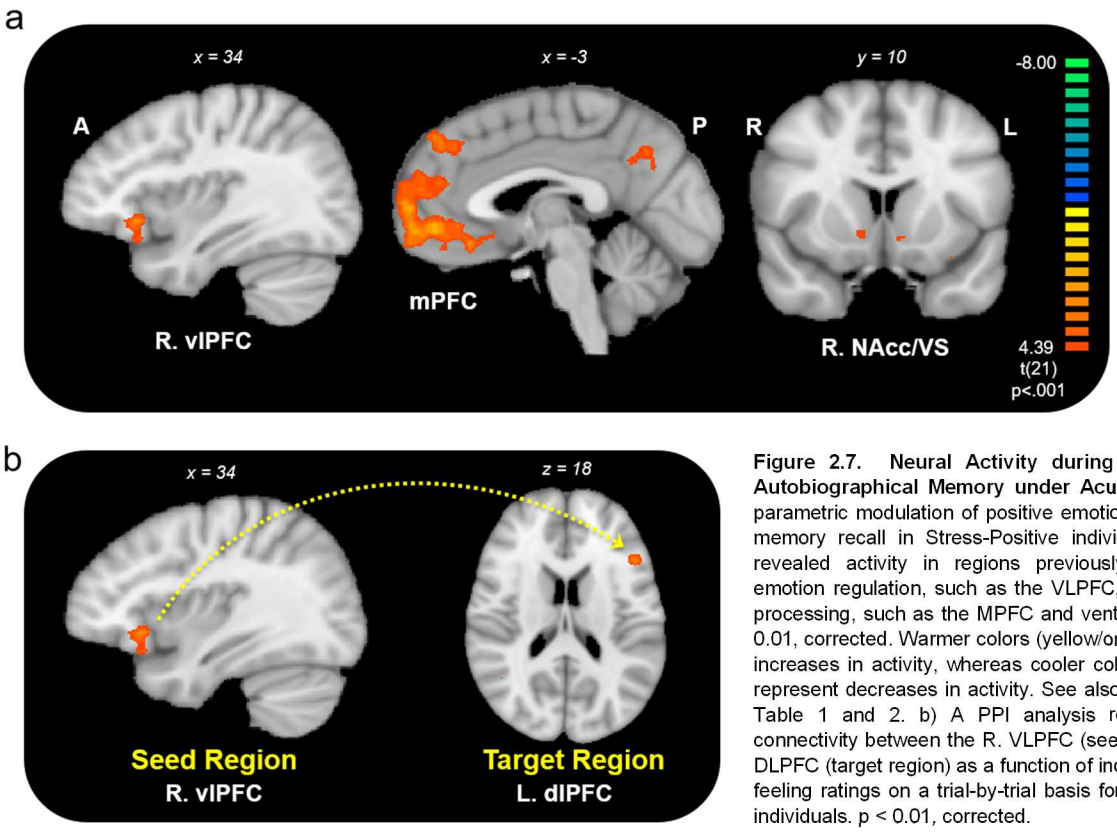


Figure 2.7. Neural Activity during the Recall of Autobiographical Memory under Acute Stress. a) A parametric modulation of positive emotion ratings during memory recall in Stress-Positive individuals (N = 22) revealed activity in regions previously implicated in emotion regulation, such as the VLPFC, and in reward-processing, such as the MPFC and ventral striatum. p < 0.01, corrected. Warmer colors (yellow/orange) represent increases in activity, whereas cooler colors (green/blue) represent decreases in activity. See also Supplementary Table 1 and 2. b) A PPI analysis revealed greater connectivity between the R. VLPFC (seed region) and L. DLPFC (target region) as a function of increasing positive feeling ratings on a trial-by-trial basis for Stress-Positive individuals. p < 0.01, corrected.

and the left DLPFC as being modulated by increases in subjective feeling ratings during recall for those who reminisced about positive, but not neutral, memories (Table 2.2).

2.6.2 VLPFC-DLPFC connectivity tracks positive feelings during memory recall

Our finding that recalling positive memories results in a dampened cortisol rise along with greater engagement of the VLPFC during positive recollection suggests that the ability to engage cortical regions involved in emotion regulation may be vital for combating stress. To explore this idea, we first conducted a psychophysiological interaction (PPI) analysis to identify neural regions that were functionally connected to the prefrontal cortex as a function of subjective feelings during positive memory recollection. We defined our VLPFC seed regions bilaterally based on our prior analyses, which showed this region being prominently activated in the *Stress-Positive* group during memory recall and in comparison to the *Stress-Neutral* group. For both seed regions, we performed a random-effects whole brain analysis for the parametric modulation of feeling ratings during recall for *Stress-Positive* individuals (using an initial threshold of $p < .001$ and the same cluster correction described above). Our PPI analysis with the right VLPFC seed (*x,y,z:* 35, 22, -3) revealed the left DLPFC (*x,y,z:* -46, 22, 18) as exhibiting greater connectivity (as a function of increasing feeling ratings) for the *Stress-Positive* group (Fig 2.7b, Table 2.3). The left VLPFC seed region yielded no target regions that reached statistical significance. To examine the relationship between functional connectivity and the physiological stress response, we tested for correlation between our PPI parameter estimates (indexing the degree of connectivity between VLPFC and DLPFC as a function of feeling ratings) and cortisol in *Stress-Positive* individuals. Although approaching significance, the association

between greater VLPFC-DLPFC connectivity and lower AUC_I cortisol levels was not significant (r_{21}= -0.35, p= .11). Taken together, our fMRI results provide converging evidence that engagement of cortical regions previously linked to emotion regulatory functions may be significant for enhancing or sustaining pleasant feelings during positive reminiscence, and thus dampening the physiological stress response.

2.7 Discussion

Acute stress elicits negative emotion (Lazarus & Folkman, 1984), lessens our ability to use cognitive emotion regulation (Raio et al., 2013), diminishes responsiveness to rewards (Bogdan & Pizzagalli, 2006), and is often a precursor to anxiety and depressive episodes (Kendler et al., 1999), making it imperative to identify effective strategies for reducing stress. Across two studies, our results showed that reminiscing about positive—but not neutral memories—buffered the physiological and emotional consequences of acute stress. Specifically, individuals who recalled positive memories showed a dampened rise in cortisol and reported lower levels of negative affect 20 min after stress exposure, resembling the non-stressed control groups. In contrast, recalling neutral memories under stress resulted in a heightened cortisol rise that is typical of the acute stress response (Kirschbaum & Hellhammer, 1994). Recalling positive memories also served to enhance mood despite stress exposure, but only for individuals with greater self-reported resiliency. For *Stress-Positive* individuals but not *Stress-Neutral* individuals, we observed greater activity in regions previously implicated in emotion regulation (e.g., VLPFC) and reward-processing (e.g., striatum) based on a parametric modulation of emotion ratings during memory recall. Further, we observed greater VLPFC-DLPFC connectivity as a function of

increasing positive emotion. Our results underscore the restorative and protective function of self-generated positive emotions in the face of stress.

The finding that positive memory retrieval restored stress-induced deficits, such as alleviating negative affect and calming the physiological stress response (i.e., HPA-axis), might suggest a role for recalling positive (but not neutral) memories in motivating a more positive perspective that interrupts the ongoing experience of a stressful event. This possibility lends support to the idea that bolstering positive emotion broadens one's cognitive perspective, in contrast to the narrowed perspective that occurs during negative affective states (Catalino & Fredrickson, 2011). Indeed, the experience of positive emotion over time helps build psychological resources for adaptive coping, making it more likely to continue experiencing positive emotions in the future, and is perhaps a potential mechanism by which resiliency is built (Ong, Bergeman, Bisconti, & Wallace, 2006). Notably, we observed that greater resiliency was associated with additional protective benefits for those who were given the opportunity to recall positive memories. This is consistent with research linking high resiliency to better adaptability to stress, such as faster cardiovascular recovery, more efficient and successful emotion regulation, and greater positive meaning finding (Ong et al., 2006; Tugade & Fredrickson, 2004).

Our fMRI results highlight the significant relationship between experiencing positive emotion, greater engagement of prefrontal regions involved in emotion regulation, and lower cortisol after stress exposure. Acute stress is well known to compromise the prefrontal cortex in humans (Arnsten, 2009), impairing self-regulation (Heatherton & Wagner, 2011), cognitive control, and task-relevant processing (Liston, McEwen, & Casey, 2009), which diminishes our ability to adapt to the environment. Consistent with

this, we did not observe prefrontal activity (VLPFC, DLPFC) in *Stress-Neutral* individuals (i.e., had higher cortisol responses). Although this null result should be treated with caution, it is noteworthy that these same regions were spared in *Stress-Positive* individuals (i.e., had lower cortisol responses), and the strength of their connectivity increased as a function of positivity. In light of this observation, we speculate that the effective use of memory recall to enhance positive emotion may serve emotion regulatory functions under stress. While it is possible that recruitment of prefrontal activity in the *Stress-Positive* group is due to more general cognitive control functioning, such as controlled memory retrieval (Badre, Poldrack, Paré-Blagoev, Insler, & Wagner, 2005), both groups underwent a recall procedure, thus supporting a more emotionally driven explanation for prefrontal engagement and suggesting a potential mechanism by which positive memory recall may contribute to stress dampening.

The VLPFC and DLPFC are thought to play pivotal yet distinct roles in successful emotion regulation, particularly cognitive reappraisal (Buhle et al., 2014; Morawetz et al., 2017). For example, a recent meta-analysis revealed that both regions were significantly activated across 48 studies examining cognitive reappraisal of primarily negative emotional stimuli (Buhle et al., 2014). The DLPFC may aid such processes as working memory and cognitive flexibility, including manipulating mental representations of affective states to regulate emotion, whereas the VLPFC may serve response selection and inhibitory functions (Robbins, 2007) and is also linked to the cognitive control of memory (Badre et al., 2005). Consistent with prior work (Morawetz et al., 2016), one possibility in our study is that the VLPFC attempts to override negative appraisals during memory retrieval, while the DLPFC helps flexibly change one's emotional state. Previous studies

have also shown an association between greater VLPFC activity and either decreased amygdala activity or increased reward-related activity (e.g., striatum) to successfully regulate emotion (Wager et al., 2008). Although we did not observe this in the present study, the link between different cortical regions and the striatum underlying regulation of positive mood (Admon & Pizzagalli, 2015), particularly with respect to stress, is an important future inquiry.

It is worth considering how the strategy of savoring positive memories to combat stress relates to other emotion regulation strategies. Mindfulness-meditation has been shown to reduce stress and promote well-being through the nonjudgmental practice of self-awareness in the present moment (Baer, 2003). Yet, physiological changes after mindfulness training are mixed as some studies show decreased cortisol whereas others show either an increase or no change (for review see Tang, Hölzel, & Posner, 2015). Variability in type and length of mindfulness training and type of stressor may help explain mixed findings, although it is difficult to speculate given the paucity of studies thus far. The core idea of mindfulness—to focus on the present rather than the past or future—may seem at odds with the strategy we propose. However, savoring the past involves deliberate attention to an enjoyable experience with the aim of cultivating positive emotions, which is distinctly different than ruminating about past negative events—a characteristic of depression. Much like mindfulness, recalling positive memories motivates a broader perspective, and perhaps directs attention away from the current stressor in favor of something more positive or relaxing. This is in contrast to strategies that focus on reinterpreting the stressor as a way to diminish its meaning (Gross, 2002), which may be less effective under stress (Raio et al., 2013). Other strategies that may buffer stress via

positive emotion include high self-esteem, receiving social support or positive feedback, and affirming personal values (Creswell et al., 2005). However, these strategies depend on situational or personality characteristics, leaving unclear their efficacy in alleviating stress in everyday life.

Our findings have broad implications for better understanding the stress response in the context of mood disorders. For instance, individuals with depression not only have difficulty in retrieving positive memories (Young et al., 2013), but are also sensitive to the effects of stress. That is, they have difficulty regulating negative emotion (Greening, Osuch, Williamson, & Mitchell, 2014), report lower levels of resilience, and have higher cortisol levels during recovery from stress (Burke, Davis, Otte, & Mohr, 2005), suggesting a critical need for understanding positive emotion deficits in depression. Thus unsurprisingly, one aim of behavioral activation therapy for depression is identifying and reengaging in positive activities that reinforce and enhance wellbeing, including positive reminiscence (Bryant, Smart, & King, 2005; Mazzucchelli, Kane, & Rees, 2010). Consistent with this idea, a recent study showed that optogenetically reactivating neural circuits associated with positive experiences in rodents can lessen depression-like behaviors caused by stress (Ramirez et al., 2015), providing

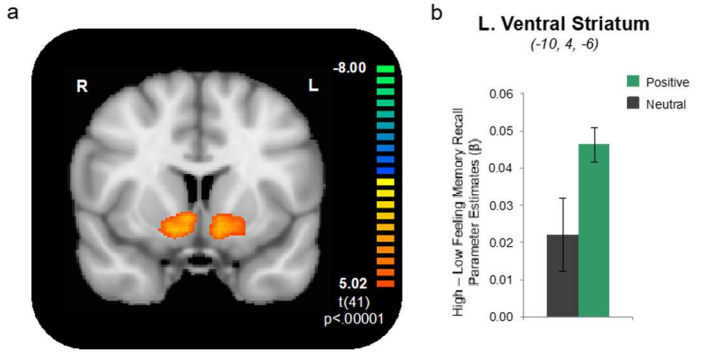


Figure 2.8. Voxels in a Ventral Striatum Monetary Reward ROI Show Greater Differential Activity between High and Low Feeling Positive Memories as Compared to Neutral Memories. a) A contrast of gain vs. loss outcomes in a card-guessing task revealed activity in the bilateral ventral striatum. $p < 0.01$; corrected. b) Mean parameter estimates from the right ventral striatum are displayed showing greater differential activity for high minus low feeling memories for the Stress-Positive compared to the Stress-Neutral group. Error bars denote SEM.

complementary evidence that thinking about the past in a positive light can recruit reward-related neural circuits in humans (Speer et al., 2014) and serve as a potentially effective way to reduce stress. In the present study, we also found that stressed individuals who recalled positive memories had a greater increase in ventral striatum activity as a function of increasing positive feelings (see Fig 2.7a), as well as for high relative to low feeling memories as compared to those who recalled neutral memories under stress (see Fig 2.8 and Table 2.4). Thus, corticostriatal circuits recruited during reminiscing about positive memories are involved in increases in positive emotion that are linked to the coping of stress. This corroborates prior work showing that individuals with lower daily cortisol output tend to be happier (Steptoe, Wardle, & Marmot, 2005) and exhibit greater sustained neural activity to positive stimuli in the striatum (Heller, van Reekum, et al., 2013). Our approach extends these findings by demonstrating that we can use something we already do naturally—recalling the positive past—to buffer the detrimental effects of acute stress in the present moment.

There are some considerations about our study that warrant mention. First, our results showed dampening of the acute stress response, but cannot necessarily speak to the effectiveness of this strategy for different stress levels. Recurrent heightened levels of cortisol observed in chronic stress can be detrimental, for instance, by suppressing the immune system, increasing susceptibility to disease (McEwen, 2007), and resulting in atrophy and reduced neurogenesis in the hippocampus, a region where memory processing and storage occurs (Sheline, 2003). Thus, it may be useful to probe if increasing positive emotions can help build psychological resources to cope with chronic stress. Second, positive memory retrieval may not be effective for everyone. There may be individual

differences leading some individuals to have fewer, less detailed or vivid positive memories or general difficulty in recalling their past (e.g., depression). This may be especially challenging for individuals who are more susceptible to stress (i.e., less resilient). Although the present study establishes positive recall as an effective stress-buffering strategy in a healthy population, it will be essential to test whether stress vulnerable individuals are able to self-generate positive memories after stress exposure and the efficacy of this strategy in sustaining reductions in negative affect and neuroendocrine responses, especially under less resilience.

It is also important to consider alternative accounts for our findings. One possibility is that greater interest, engagement or even distraction during positive relative to neutral recall may explain cortisol differences. Yet, we found this not to be the case (as measured by vividness ratings and recall duration; see Supplementary Results). There is also evidence to suggest that distraction alone does not lead to stress dampening, as stress participants who perform highly distracting working memory tasks still exhibit the typical cortisol rise (Schoofs et al., 2009). Additionally, given that all participants recalled past experiences to elicit positive emotion, it is unclear whether other strategies aimed at increasing positive emotion would also be effective. For instance, positive feelings may be enhanced by engaging in positive mental time travel about the future (Quoidbach et al., 2009). Another such strategy is the use of positive imagery, which may be effective for mitigating pain (Fardo, Allen, Jegindø, Angrilli, & Roepstorff, 2015). However, in a prior study we found positive imagery to be less effective than positive memory retrieval in enhancing mood (Speer et al., 2014), which may be vital for reducing stress. Finally, while our focus was to examine the stress-buffering nature of positive reminiscence, it is also

important to note that stress can be beneficial in certain contexts. Specifically, stress hormones (e.g., cortisol) exhibit an inverted U-shaped response curve, such that extreme levels (both low and high), but not moderate levels, impair cognitive performance including memory (Diamond, Bennett, Fleshner, & Rose, 1992; Joels, 2006). Such cortisol effects on performance can further depend on age (Lupien et al., 2002; Lupien et al., 2002), exposure to novelty (Okuda, Roozendaal, & McGaugh, 2004), and the presence of other hormones, such as oxytocin. Oxytocin, for instance, may have been a positive mediator in the present study given its role in modulating fear and anxiety (Leuner, Caponiti, & Gould, 2012). While beyond the scope of the current study, future work could explore the role of varying levels of cortisol and other stress-modulating hormones on the emotion regulatory function of positive recall.

Although stress can be adaptive for learning and cognitive performance (Lupien, Maheu, Tu, Fiocco, & Schramek, 2007), sometimes our stress response (e.g., panic attack) is out of proportion to the stressor (e.g., studying for a test), compromising our ability to use cognitive emotion regulation skills we already know (Raio et al., 2013). Our results highlight a more proactive way to alleviate stress. Rather than attempting to decrease negative feelings or deliberately reinterpret the meaning of a stressful experience, which may be effective in only certain contexts or for particular individuals (Troy, Wilhelm, Shallcross, & Mauss, 2010), one might focus on increasing positive feelings instead. We demonstrate that this can even be done with a strategy—recalling pleasant memories—that is unrelated to the stressor. When uncontrolled, psychological stress can drive us far from a desirable state. Enhancing positive feelings when reminiscing about the past may be one way to bring us back.

Chapter 3: Finding Positive Meaning in Past Negative Events Adaptively Updates Memory [Experiments 3-6]

3.1 Introduction

We all have memories we might want to forget. Vividly recalling negative experiences from the past can retrigger those same painful feelings all over again (Bower, 1981)—like the sting of an unexpected loss or the disappointment of a crushing failure. Although remembering such events can be adaptive for survival (e.g., preventing future mistakes), it can be maladaptive when we fixate on these negative feelings and ruminate about the situation—a key feature of anxiety, depression, and stress-related disorders (American Psychiatric Association, 2013). Negative autobiographical memories of high personal significance and arousal in particular can induce a stronger sense of re-living the actual event, which contributes to the retention and intrusion of such memories and further exacerbates clinical symptomology (Brown & Kulik, 1977; Holland & Kensinger, 2010; K. Young et al., 2013). Therefore, identifying effective ways to cope with lingering negative memories is of critical importance.

One potential way to alter how we feel about past adversity is to find positive meaning in it. In fact, finding more adaptive ways to reframe negative events is central to therapeutic techniques, such as cognitive behavioral therapy (Beck, 2011). Its frequent use in everyday life is linked to fewer depressive symptoms, more positive emotionality (Gross & John, 2003), and faster emotional and physiological recovery from stress (Tugade & Fredrickson, 2004). However, an unexplored but intriguing question is whether finding

positive meaning in a past negative event actually changes the memory representation itself.

Memory is reconstructed at the time of retrieval (Tulving, 2002), leaving the potential for modification each time it is reopened, and allowing for new information to update the old through a reconsolidation process (Lee et al., 2017; Nader & Einarsson, 2010). Memory updating is thought to most readily occur when the intervening information triggers a prediction error, or a mismatch between what is expected and what occurs (Krawczyk et al., 2017; Sevenster et al., 2014). Evidence of successful updating has been observed for conditioned fear memories in both rodents and humans (Nader & Hardt, 2009; Nader et al., 2000; Schiller et al., 2010). For instance, reactivating fear memories and then introducing non-fearful information (i.e., extinction) prevented the return of fear at future retrieval (24h later), demonstrated by reduced physiological arousal (Schiller et al., 2010) and dampened neural activity associated with fear (amygdala) (Agren et al., 2012) and emotion regulation (prefrontal cortex) (Schiller, Kanen, Ledoux, Monfils, & Phelps, 2013). There is similar evidence for updating procedural (Jones et al., 2012; Walker et al., 2003) and episodic memory (De Brigard, Hanna, St Jacques, & Schacter, 2018; Goltseker et al., 2017; Hupbach et al., 2007; James et al., 2015).

Along these same lines, can positive emotion-focused coping successfully update negative autobiographical memories? Conceivably, focusing on the bright side (e.g., learning better study skills) of a past negative memory (e.g., failing an exam) after retrieval could lead to the updating and subsequent re-emergence of such positivity the next time the memory is retrieved. In turn, this could lessen the experience of negative emotion associated with future recollections, highlighting the potential benefits of positive meaning

finding, not just for regulating in the present, but also for modifying our future emotional response.

Across four experiments, we asked whether finding positive meaning in a past negative event could adaptively update that memory with positive content, subsequently changing how we feel (emotional feelings induced by the memory) and what we remember (content of the memory) in the future. Experiment 1 tested the strategy of interest—positive meaning finding—against potential alternatives: analyzing or focusing on a memory's negative aspects (similar to rumination), focusing on a memory's neutral aspects (similar to minimizing reappraisal or distancing oneself), or distraction. We tested for successful updating at retrieval 1-week later (Experiment 3) and its durability after 2-months (Experiment 4). We then examined the mechanism by which negative memories are updated with positive content, specifically testing whether positive meaning finding utilizes reconsolidation updating mechanisms (Experiment 5) (Lee et al., 2017). Finally, we examined whether the self-relevant and meaningful context of the positive meaning finding strategy mattered for updating, by comparing it to an extrinsic reward (e.g., money) that similarly increased positive emotion after retrieval but was irrelevant to the recollected memory (Experiment 6).

3.2 Experiment 3: Methods

3.2.1 Participants

131 healthy young adults participated in this 2-day study. Exclusions included failure to return for the second session (N=4), computer issues (N=1), and poor performance on the memory recall tasks (did not recall specific negative memories, N=12;

remembered <50% of memories from Day 1; N=12). The final sample included 102 participants (35 men; Mean age= 20.3; SD= 2.9) who were randomly assigned to four experimental groups: *Negative* (N=25; 9 men), *Positive* (N=26; 8 men), *Neutral* (N=25; 8 men), and *Distraction* (N=26; 10 men). Our target sample size was 100 participants (25 per group) based on a power analysis using pilot data expecting 80% power. Participants gave informed consent in accordance with the Rutgers Institutional Review Board for Protection of Human Subjects and received partial course credit and monetary compensation for participating.

3.2.2 Experimental Design

Day 1: Memory Recall 1 and Elaboration. Participants first completed questionnaires asking about their depressive and anxiety symptoms (Mood and Anxiety Symptom Questionnaire, MASQ; Watson et al., 1995), their ability to savor positive emotions in daily life (Emotion Regulation Profile Revised, ERP-R; Nelis, Quoidbach, Hansenne, & Mikolajczak, 2011), social and positive coping strategies (COPE Inventory; Carver, 2013), use of cognitive reappraisal and suppression (Emotion Regulation Questionnaire, ERQ; Gross & John, 2003), trait resilience (Connor-Davidson Resiliency Scale, CD-RISC; Connor & Davidson, 2003), and recent life stress (Perceived Stress Scale, PSS; Cohen, Karmarck, & Mermelstein, 1983).

Next participants were given a list of 30 life event cues (e.g., Family Vacation) and indicated which cues triggered a specific negative memory. They then performed a memory recollection and elaboration task using 12 event cues randomly selected from that list. On each trial of this task, they saw one event cue (e.g., Witnessing an accident) and wrote 3-5

sentences describing what happened in that memory, followed by emotion ratings for feeling (How does this make you feel in the present moment? 11-point scale: -5= extremely negative, 0= neutral, 5= extremely positive), intensity (How emotionally intense is this memory? 5-point scale: 1= not intense, 5= extremely intense), vividness (How clearly can you see this memory in your mind? 5-point scale: 1= not vivid; 5 = extremely vivid), and age of the memory (How long ago did this occur?).

Afterwards, they wrote an additional 3-5 sentences elaborating on the memory. Depending on group assignment, they either focused on the positive aspects (*Positive* group), negative aspects (*Negative* group), or neutral aspects (*Neutral* group) of the memory. The *Distraction* group did not elaborate and instead performed a spatial perception task for 60s after memory recall and ratings. This involved seeing an arrow and answering whether it was pointing to the left or right. This task has been used as a control condition in prior emotion regulation studies (Kross et al., 2009). Immediately before and after the Recall 1 and Elaboration tasks, participants rated their current mood state via the Positive and Negative Affective Schedule (PANAS; Watson, Clark, & Tellegen, 1988).

Day 2: Memory Recall 2. Participants returned 1-week later for a follow-up memory recollection test for the same 12 memories. They provided a written description (3-5 sentences) and emotionally rated (feeling, intensity) each memory again. Like Day 1, participants rated their current mood state via the PANAS before and after the recall 2 task (see Fig 3.1 for timeline).

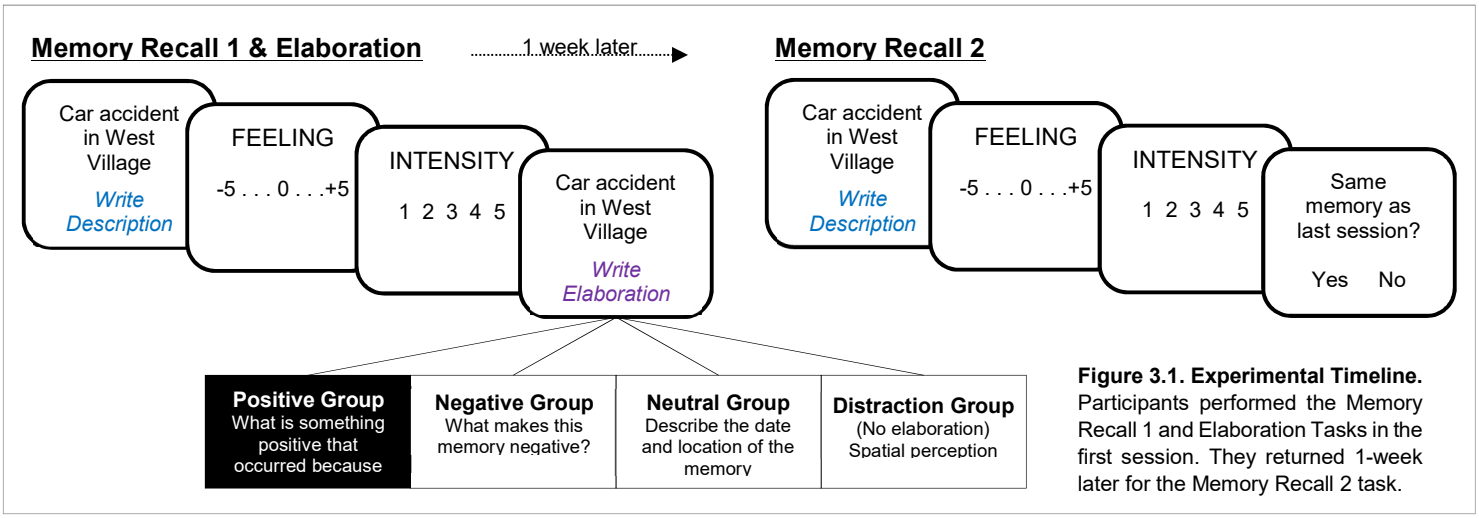


Figure 3.1. Experimental Timeline. Participants performed the Memory Recall 1 and Elaboration Tasks in the first session. They returned 1-week later for the Memory Recall 2 task.

3.2.3 Data Analysis

To first verify that participants followed directions, two independent raters read the written descriptions from the memory Recall 1, Elaboration, and Recall 2 tasks. Memories were excluded from analysis if they were a) general instead of specific; b) not negative during the Recall 1 task, or; c) if participants failed to follow directions during the Elaboration task. Participants who did not have at least 8 out of 12 memories were excluded from analysis.

To assess change in emotion from before to after the Elaboration task, we created difference scores (Recall 2 – Recall 1) across sessions for feeling and intensity ratings, separately. To test for group differences in emotion change, we performed one-way ANOVAs examining feeling and intensity (separately) by group.

We also analyzed written memory descriptions for changes in content from before to after the Elaboration task. Two independent raters made subjective ratings of positivity (1 = not at all positive; 10 = extremely positive) based on language use and tone of descriptions from all three tasks, degree of dissimilarity in the content between retrievals

(1 = extremely similar; 10 = extremely dissimilar) and ratings of meaningfulness for written elaborations (How meaningful or significant is this? 1 = not at all significant; 10 = extremely significant). Inter-rater reliability was high (cronbach's alpha = 85.4%). We then calculated a difference score for each content variable across sessions (Recall 2 – Recall 1), and performed one-way ANOVAs by group. Within the Positive group, we additionally performed correlations between feeling change and a) content during elaboration (positivity, meaningfulness), b) changes in positive content and c) dissimilarity in content across retrieval sessions.

We followed up significant effects with post-hoc t-tests. All tests were two-tailed and had an alpha level of .05.

3.3 Experiment 3: Results

3.3.1 Negative autobiographical memory retrieval

On average, participants spent 2.46 minutes (SD= 1.03) writing descriptions for Recall 1, 1.47 minutes (SD= 0.68) writing elaborations and 1.97 minutes (SD= 0.87) writing descriptions for Recall 2. Recall/elaboration durations and the number of memories utilized in analyses (M= 8.70, SD= 1.83) did not differ by group (all $p>.53$). There were also no group differences in mood or baseline ratings of feeling, intensity, vividness or age of the memories during Recall 1 (all $p> .17$), suggesting that participants recalled memories of similar emotional quality and spent a similar amount of time thinking and writing about them, regardless of group assignment.

3.3.2 Positive meaning finding leads to enhanced positive emotion at future retrieval

We first tested whether our regulation strategy of interest—positive meaning finding—was indeed more positive and meaningful in content than the other elaborations (focusing on negative or neutral aspects). As expected, one-way ANOVAs for ratings of positivity and meaningfulness (made by independent raters) during the Elaboration phase by group were significant (positivity: $F_{2,73}$= 171.75, p< .001, η^2= 0.825; meaning: $F_{2,73}$= 41.46, p< .001, η^2= 0.532) and post-hoc t-tests confirmed that the *Positive* group wrote elaborations that were more positive and meaningful than the *Negative* and *Neutral* groups (positivity: t_{49}= 19.27, p< .001, d= 5.40; t_{49}= 7.47, p< .001, d= 2.10; meaning: t_{49}= 6.19, p< .001, d= 1.74; t_{49}= 8.23, p< .001, d= 2.30). The *Neutral* group was more positive and less meaningful than the *Negative* group (positivity: t_{48}= 11.68, p< .001, d= 3.34; meaning: t_{48}= -3.24, p= .002, d= 0.91).

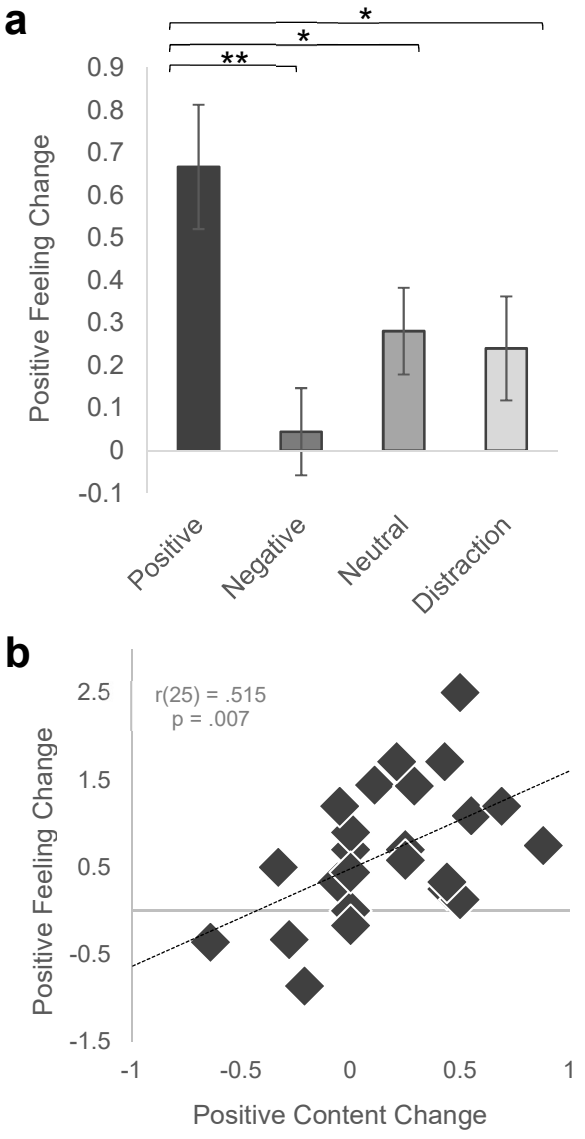


Figure 3.2. Positive emotion change across groups. a) The Positive group showed the greatest increase in positive emotion across sessions compared to the three other groups. b) Within the Positive group, individuals with the greatest increase in positive emotion showed the greatest increase in positive memory content over time. *p<.05; **p<.01

A key hypothesis was that finding positive meaning in past negative events would elicit the greatest change in feeling across retrievals. A one-way ANOVA for change in feeling (Recall2 – Recall1) by group revealed a significant main effect of group, $F_{3,98}$= 4.67, p= .004, η^2= 0.125. Post-hoc t-tests showed that the *Positive* group had the greatest increase in positive emotion at future retrieval as compared to all other groups (*Negative*: t_{49}= 3.44, p= .001, d= 0.98; *Neutral*: t_{49}= 2.15, p= .036, d= 0.62; *Distraction*: t_{50}= 2.24, p= .030, d= 0.63), whereas the three other groups did not differ from each other (all p> .12; see Fig 3.2a). Importantly, this effect was not driven by gender, mood, recall duration, or baseline ratings of feeling, intensity, vividness, or age of the memories (all p> .17). A one-way ANOVA for change in intensity (recall2 – recall1) by group was not significant (p= .69).

3.3.3 Increases in positive emotion track changes in memory content over time

We also tested whether change in content across retrievals was most pronounced in the *Positive* group. The one-way ANOVA for change in positive content (Recall2 – Recall1) was trending ($F_{3,98}$= 2.30, p= .082) and for content dissimilarity across retrievals it was non-significant ($F_{3,98}$= 1.28, p= .286). Given our specific hypothesis that using positive meaning finding, in particular, would lead to greater changes in memory content over time (in terms of greater positivity and also greater dissimilarity in event details), we performed correlations between these variables within the *Positive* group only. A greater increase in positive feeling across retrievals was associated with a) a greater increase in positive memory content (r_{25}= .515, p= .007) and b) greater dissimilarity in memory content (r_{25}= -.455, p= .02; Fig 3.2b). That is, the degree to which memories elicited greater

positive emotions tracked changes in memory content over time, in terms of content becoming both more positive and less similar than before.

3.4 Replication and Longitudinal Extension

Experiment 3 showed that positive meaning finding led to an increase in positive emotion, which tracked increased positive memory content at future retrieval, whereas focusing on negative aspects, neutral aspects, and distraction did not. The goal of Experiment 4 was to replicate this finding in a larger sample who used positive meaning finding and, importantly, to test the longevity of the effect over the course of 2-months. A key change in the experimental design is that we tested the positive meaning finding strategy against natural recollection—a condition to control for memory rehearsal without the intention of modification.

3.5 Experiment 4: Methods

3.5.1 Participants

128 healthy young adults participated in this online 3-session longitudinal study. Exclusions included failure to complete the second (N=20) or third session (N=11) or poor performance on the memory recall tasks (did not recall specific negative memories, N=2; difficulty using positive meaning finding, N=4). The final sample included 91 participants (39 men; Mean age= 20.9; SD= 3.89) who were randomly assigned to two experimental groups: *Positive* (N=46; 20 men) and *Control* (N=45; 19 men). Our target sample size was 90 participants (45 per group) based on a power analysis using pilot data expecting 80% power (for detecting differences in memory content). Participants gave informed consent

in accordance with the Rutgers Institutional Review Board for Protection of Human Subjects and received partial course credit and/or monetary compensation for participating.

3.5.2 Experimental Design

This study mirrored Experiment 3 but was modified to include a 3rd session (2-months later) and only had two groups (*Positive*, *Control*). All sessions were conducted online using Qualtrics surveys. In session 1, participants first completed questionnaires asking about demographics, emotion, mood, and clinical symptoms. These included the same questionnaires as in Experiment 3 as well as the social connectedness scale (Lee & Robbins, 1995), ten-item personality inventory (TIPI; Gosling, Rentfrow, & Swann, 2003), social avoidance and distress scale (SAD; Watson & Friend, 1969), Ruminative Responses Scale (RRS; Treynor, Gonzalez, & Nolen-Hoeksema, 2003), Subjective Happiness Scale (Lyubomirsky & Lepper, 1999), Satisfaction with life scale (Diener, Emmons, & Larsen, 1985), and Interpersonal Regulation Questionnaire (IRQ; Williams, Morelli, Ong, & Zaki, 2018).

Participants were then given a list of common life event cues (e.g., Family vacation) to help them trigger 10 different, specific negative autobiographical memories from their past. For each memory they provided a specific keyphrase to be used in future sessions, a 3-5 sentence description of the memory, and ratings of feeling, intensity, vividness, significance, social closeness, frequency of recall, and date of the memory. Afterwards they elaborated further on the same memories. Depending on random group assignment, they either wrote an additional 3-5 sentences focusing on the positive aspect of the memory (*Positive* group) or recalled it naturally again (*Control* group).

Session 2 occurred 1 week later (M_{days}= 7.70, SD= 2.31) and session 3 occurred 2 months later (M_{days}= 54.5, SD= 6.10). In sessions 2 and 3, participants saw their same 10 keyphrases, described each memory in 3-5 sentences, and made emotion ratings (feeling, intensity, vividness, significance, and social closeness). In session 3, we also asked the degree to which participants talked about (in person, text/phone, or on social media), thought about, focused on the positive aspects, and focused on the negative aspects of their memories over the past 2-months, and assessed clinical symptoms again via the MASQ to measure changes over time. To control for mood effects, positive and negative mood were assessed before and after memory recollection in all three sessions.

3.5.3 Data Analysis

Data analysis procedures mirrored that of Experiment 3 with a few modifications. In addition to difference scores after 1-week (Recall 2 – Recall 1), we calculated an additional difference score for each dependent variable at 2-months relative to the first session (Recall 3 – Recall 1). To examine the effects of memory ratings and content across time, we conducted time (1-week, 2-months) by group (*Positive*, *Control*) ANOVAs for each dependent variable, and then followed up significant effects with post-hoc t-tests. All tests were two-tailed and had an alpha level of .05. Memory content was judged by two independent raters on the same characteristics of positivity, meaningfulness, and dissimilarity.

3.6 Experiment 4: Results

3.6.1 Changes in emotion and memory content are long-lasting

We first examined changes in feeling ratings after 1-week and 2-months. A time (1-week, 2-months) by group (*Positive*, *Control*) ANOVA for feeling rating change yielded a significant main effect of time ($F_{1,89}$= 7.02, p= .01, η^2= .073) and main effect of group ($F_{1,89}$= 8.97, p= .004, η^2= .092), but no interaction (p= .802). Post-hoc t-tests showed that although both groups had a greater emotion change after 2-months as compared to 1-week (t_{90}= 2.66, p= .009, d= 0.27), the *Positive* group had a greater increase in positive emotion than the *Control* group at both the 1-week (t_{89}= 2.49, p= .015, d= 0.525) and 2-month delays (t_{89}= 2.59, p= .011, d= 0.541; Fig 3.3a left panel). A similar analysis for vividness yielded a main effect of time ($F_{1,89}$= 23.15, p< .001, η^2= 0.216) and a trending main effect of group ($F_{1,89}$= 3.08, p= .103, η^2= 0.03), suggesting a greater reduction in vividness as more time passed and a trend towards a greater reduction in the *Positive* group. For intensity and meaningfulness, there was only a significant main effect of time ($F_{1,89}$= 12.32, p= .001, η^2= 0.146; $F_{1,89}$= 6.68, p= .011, η^2= 0.08) demonstrating a greater reduction in intensity and meaningfulness over time, regardless of group.

We also examined changes in the positivity and dissimilarity of memory content over time, based on judgments from independent raters. A time (1-week, 2-months) by group (*Positive*, *Control*) ANOVA for change in positive content yielded a significant main effect of time ($F_{1,89}$= 27.48, p< .001, η^2= 0.236) and main effect of group ($F_{1,89}$= 6.05, p= .021, η^2= 0.058), but no interaction (p= .677). Post-hoc t-tests showed that although both groups had more positive content after 2-months as compared to 1-week (t_{90}= 5.27, p< .001, d= 0.651), the *Positive* group had a greater increase in positive content than the

Control group at both the 1-week (t_{89}= 2.32, p= .023, d= 0.498) and 2-month delays (t_{89}= 2.12, p< .037, d= 0.446; Fig 3.3a middle panel). A parallel analysis for dissimilarity in content across retrievals revealed the same pattern of results (main effect of time: $F_{1,89}$= 90.08, p< .001, η^2= 0.503; main effect of group: $F_{1,89}$= 10.80, p= .001, η^2= 0.108; no interaction: p= .975), demonstrating greater dissimilarity in memory content for the *Positive* relative to the *Control* group at both time points (1-week: t_{89}= -3.48, p= .001, d= 0.723; 2-months: t_{89}= 2.89, p= .005, d= 0.607; Fig 3.3a right panel).

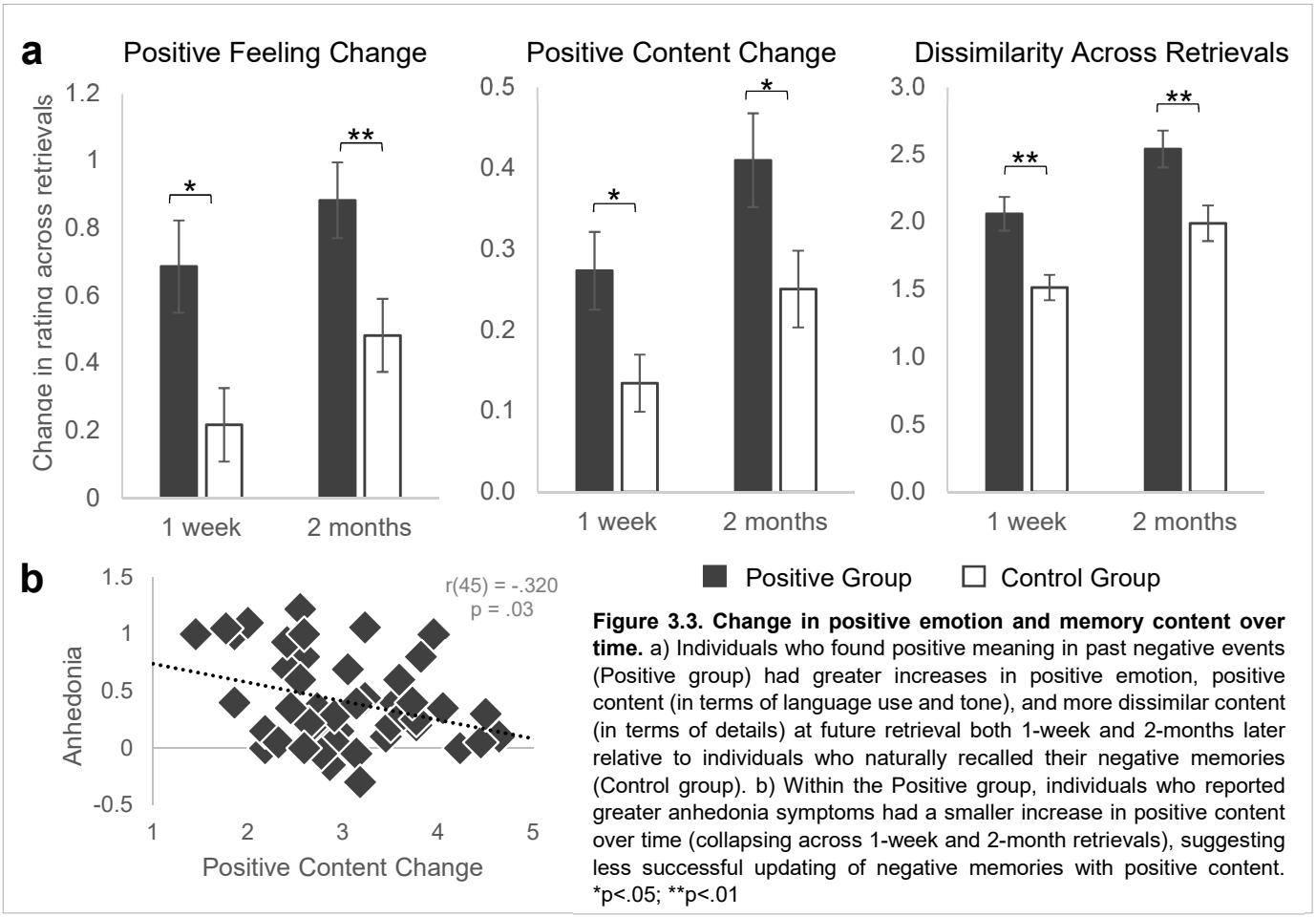


Figure 3.3. Change in positive emotion and memory content over time. a) Individuals who found positive meaning in past negative events (Positive group) had greater increases in positive emotion, positive content (in terms of language use and tone), and more dissimilar content (in terms of details) at future retrieval both 1-week and 2-months later relative to individuals who naturally recalled their negative memories (Control group). b) Within the Positive group, individuals who reported greater anhedonia symptoms had a smaller increase in positive content over time (collapsing across 1-week and 2-month retrievals), suggesting less successful updating of negative memories with positive content. *p<.05; **p<.01

3.6.2 Individual differences

Within the *Positive* group we also tested for individual differences that might relate to one's success in changing their emotion or memory content over time, specifically looking at clinical symptomology (depression, anhedonia). Interestingly, individuals reporting fewer anhedonia symptoms showed the greatest increase in positive content across retrievals (r_{45}= -.320, p= .03; Fig 3.3b), suggesting that experiencing anhedonia—the loss of pleasure or desire in things once enjoyed—may relate to poorer success in effectively changing negative memories into more positive ones over time.

These results replicate and extend Experiment 3, demonstrating that positive meaning finding not only changes the emotion it elicits at future retrieval but also the content of the memory. Further, it can leave a longer-lasting mark on negative memories, as such changes were still present 2-months later.

3.7 Reconsolidation as the Updating Mechanism

The goal of Experiment 5 was to then uncover the specific mechanism by which positively elaborating on a negative memory leads to beneficial changes. We hypothesized that this memory updating may take advantage of the reconsolidation process. In a typical reconsolidation paradigm, memory is reactivated and then interference occurs during the reconsolidation window (up to 6h after reactivation) (Lee et al., 2017). A memory test to determine whether the memory has been modified occurs after a delay—typically 24h—to give time for memory to restabilize. Thus, Experiment 5 follows this paradigm, whereby individuals reactivate negative memories (via mental recall) followed by the manipulation

(i.e., positive meaning finding), and then changes in the memories (i.e., feeling change) are tested after a 24h delay (*Delayed-Test* group).

However, because reconsolidation is a time-dependent process, memory updates should only be observable a) if the memories were reactivated prior to the manipulation and b) after reconsolidation has ended (e.g., after a delay) but not immediately after the manipulation (Nader, 2015). Thus, one control group did not reactivate their memories prior to the manipulation (*No-Reminder* group) and another control group was tested shortly after the manipulation (*Immediate-Test* group). Importantly, across all groups, half of the memories were recalled naturally as a control for comparison with the memories that underwent the positive manipulation. Our prediction is that only individuals who reactivated their memories prior to the positive manipulation and were tested after a 24h delay (*Delayed-Test* group) should show evidence of an update in the memory (as indexed by changes to feeling ratings). Since reconsolidation should be dependent on reactivation, if positively elaborated memories in the *No-Reminder* group show a feeling change at test, this would suggest the prevalence of a new memory, potentially competing with the old, rather than or in addition to an update to the original memory. Likewise, if this occurs in

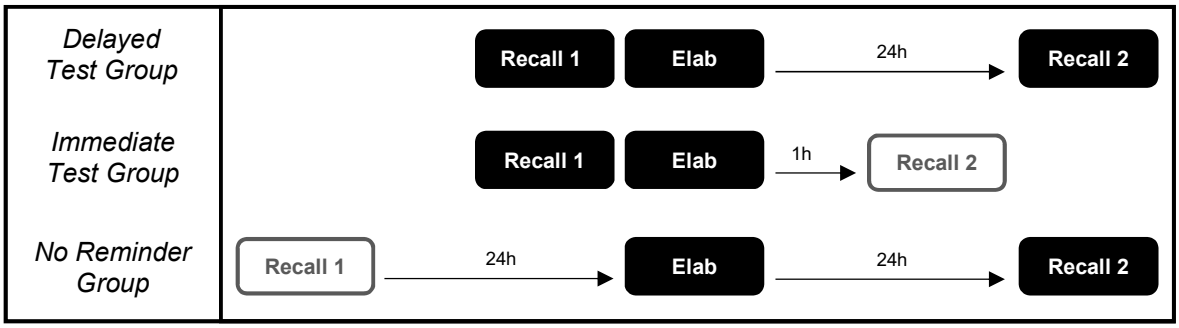


Figure 3.4. Timeline for Experiment 5. All three groups first reactivated 32 negative autobiographical memories in the Recall 1 task, performed the Elaboration task involving positive meaning finding (positive condition) and natural recall (control condition), and then recalled the same memories again in the Recall 2 task. The Delayed-Test and Immediate-Test groups reactivated their memories and modified them during the reconsolidation window, but were tested after either a 24h (Delayed-Test; measures reconsolidation updating) or 1h delay (Immediate-Test; measures short-term memory). The No-Reminder group reactivated their memories outside the reconsolidation window (24h earlier) and were tested 24h later (measures new memory generation).

the *Immediate-Test* group, it would suggest that this manipulation also influences short-term memory, rather than being specific to the long-term memory we were attempting to update (see Fig 3.4 for timeline).

3.8 Experiment 5: Methods

3.8.1 Participants

104 healthy young adults participated in this multi-session study. Exclusions included failure to return for the second or third session (N=11; due to adverse weather, N=1), computer issues (N=3), and poor performance on the memory recall tasks (did not recall specific negative memories, N=4; remembered <50% of memories from Day 1, N=6; difficulty using positive meaning finding, N=7). The final sample included 72 participants (29 men; Mean age= 22.3; SD= 6.54) who were randomly assigned to three experimental groups: *Delayed-Test* (N=23; 10 men), *Immediate-Test* (N=25; 10 men), and *No-Reminder* (N=24; 9 men). Our target sample size was 75 participants (25 per group) based on a power analysis using pilot data expecting 80% power. Participants gave informed consent in accordance with the Rutgers Institutional Review Board for Protection of Human Subjects and received partial course credit and/or monetary compensation for participating.

3.8.2 Experimental Design

Day 1: Autobiographical Memory Questionnaire. On Day 1, all participants first completed questionnaires asking about emotion, mood, and personality traits as described in Experiment 3. They then completed an autobiographical memory questionnaire (AMQ). They saw 68 event cues (e.g., Witnessing an accident) that could trigger a specific negative

memory from their past (e.g., Car accident in West Village). For each cue, they thought of a negative memory, wrote a brief description (1-2 sentences), provided a date (How long ago did this memory occur?), and made subjective ratings of feeling, emotional intensity, vividness, significance and social closeness (How close do you feel to the people who were in the memory with you? 1 = not close or alone; 5 = extremely close). Importantly, participants also created a unique keyphrase (5–10 words) for each memory to facilitate recollection at future retrievals. The experimenter randomly selected 32 memories from each participant's AMQ that were deemed as negative and occurred at a specific place and time (the minimum criteria for inclusion). Memories were then matched in feeling and intensity ratings and each pair was randomly assigned to the positive or control condition to ensure that memories were similar in each condition at baseline.

Day 2-3: Memory Recall 1, Elaboration, and Memory Recall 2. All three groups of participants retrieved 32 negative memories via mental recall as a means of reactivation (Recall 1 task). On each trial, they saw one unique keyphrase for 14 sec, made button presses indicating recall duration, and made ratings of feeling and emotional intensity.

Afterwards they performed an Elaboration task that included the positive manipulation. On each trial, they saw the same unique keyphrases again for 20 sec. They were asked to find positive meaning in the negative memory for half of the memories (16 positive trials) and to naturally recall the other half (16 control trials). After a positive trial, they were asked: Were you able to think of something positive associated with this memory? (Yes or No). After a control trial, they were asked: Did you think about the specified memory? (Yes or No). There were 2 positive blocks and 2 control blocks with 8 trials each. Blocks were presented in counterbalanced order across participants. Two

groups (*Delayed-Test* and *Immediate-Test*) reactivated the memories prior to the positive elaboration manipulation (during the reconsolidation window), whereas the third group (*No-Reminder*) did not reactivate the memories beforehand (delay of 24h between reactivation and elaboration).

To assess changes in memory, all participants returned to recall the same 32 memories again via mental recall and make subjective emotion ratings (Recall 2 task). Importantly, on each trial they were also asked whether they recalled the same memory as in the prior session. This ensured that observed changes in memories were due to memory updating and not due to participants choosing to recall different memories during Recall 2. Two groups (*Delayed-Test* and *No-Reminder*) returned for Recall 2 after a 24h delay, whereas the third group (*Immediate-Test*) returned after only a 1h delay (during the reconsolidation window). To assess mood, participants reported their current mood state via the PANAS before and after each task.

3.8.3 Data Analysis

Memories were only included in analyses if participants reported that a) they thought about the same specific event across all retrievals and b) they were successful in using positive meaning finding (for positive trials). Participants who did not have at least 8 out of 16 memories in a particular condition (positive, control) were excluded from analysis.

To assess change in emotion from before to after the elaboration task, we created difference scores (Recall 2 – Recall 1) across sessions for feeling ratings for each condition (positive, control) separately. We then performed a condition (2: positive, control) by group

(3: *Delayed-Test*, *Immediate-Test*, *No-Reminder*) ANOVA for feeling change. We followed up significant effects with post-hoc t-tests. All tests were two-tailed and had an alpha level of .05.

3.8 Experiment 5: Results

A condition (2: positive, control) by group (3: *Delayed-Test*, *Immediate-Test*, *No-Reminder*) ANOVA for feeling change revealed a significant interaction ($F_{2,69}$= 4.115, p= .02, η^2= 0.107). Examining simple effects (differential feeling change for positive – control trials) between groups indicated that the *Delayed-Test* group had a significantly greater increase in positive emotion for positive relative to control trials as compared to the *Immediate-Test* (t_{46}= 2.57, p= .014, d= .745) and *No-Reminder* (t_{45}= 2.27, p= .028, d= .665)

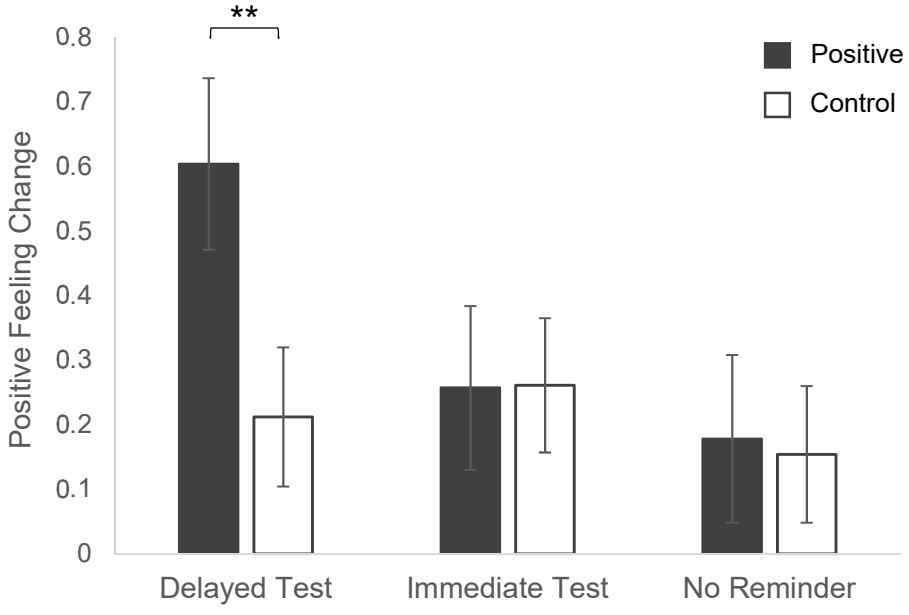


Figure 3.5. Positive meaning finding leverages reconsolidation update mechanisms. Only the Delayed-Test group—individuals who underwent the positive manipulation after reactivation and were tested after a 24h delay—showed an increase in positive emotion for positive but not control trials at future retrieval, supporting a reconsolidation updating account. Individuals who were not tested after a delay (Immediate-Test group) and did not reactivate their memories prior to the positive manipulation (No-Reminder group) showed no difference between positive and control trials at future retrieval. *p<.05; **p<.01

groups, who showed no such changes and also did not differ from each other (t_{47}= 0.192, p= .85, d= .055; Fig 3.5). Importantly, there was no difference in memory onset or recall duration between groups in any of the three sessions (all p>.135), suggesting similar ease of retrieval across groups despite methodological differences in timing of recall (1h vs. 24h later). Memories also did not differ in initial ratings of feeling, intensity, social context, vividness, or age of memories across conditions prior to memory modification (all p>.296). These results suggest that positive meaning finding updates negative memory by co-opting mechanisms of reconsolidation.

3.10 Positive Meaning Finding vs. Monetary Reward for Memory Modification

Experiment 3-5 demonstrated that positive meaning finding leads to enhanced positive emotion at future retrieval—at both shorter (24h, 1-week) and longer (2-months) delays. Experiment 5 provided additional evidence that this adaptive updating may occur via reconsolidation. One outstanding question is whether other manipulations that increase positive emotions would similarly update memory. That is, is the generation of positive emotion alone sufficient to update memory, or does the meaningful context of a positive elaboration matter? Thus, Experiment 6 tested whether another positive emotion inducing manipulation—receiving an extrinsic reward of money—after negative memory retrieval would lead to increased positivity at future retrieval similar to a more internally generated manipulation like positive meaning finding.

3.11 Experiment 6: Methods

3.11.1 Participants

69 healthy young adults participated in this 2-day study. Exclusions included failure to return for the second session (N=5; due to adverse weather, N=1), computer issues (N=3), and poor performance on the memory recall tasks (did not recall specific negative memories, N=3; difficulty using positive meaning finding, N=2). The final sample included 56 participants (18 men; M_{age}= 21.5; SD= 6.33) who were randomly assigned to two experimental groups: *Positive* (N=28; 9 men) and *Money* (N=28; 9 men). Our target sample size was 56 participants (28 per group) based on a power analysis using pilot data expecting 80% power. Participants gave informed consent in accordance with the Rutgers Institutional Review Board for Protection of Human Subjects and received partial course credit and/or monetary compensation for participating.

3.11.2 Experimental Design

This study followed the same design as the *Delayed-Test* group in Experiment 5 but was modified to fit into 2 sessions. On Day 1, participants filled out 1) emotion/mood questionnaires, and then completed 2) the AMQ, 3) Recall 1 task, and 4) the Elaboration task. To reduce the potential for fatigue, the Recall and Elaboration tasks only included 20 negative memories (12 positive trials; 8 control trials), instead of 32. In the Elaboration task, the *Positive* Group either positively elaborated on the negative memories (positive trials) or recalled naturally (control trials), whereas the Money Group received $0.50 during negative recall (positive trials) or recalled naturally (control trials). All participants

returned 24h later to complete the recall 2 task, which was identical to Experiment 5 except with only 20 trials.

3.11.3 Data Analysis

Like previous experiments, we calculated difference scores across time (Recall 2 – Recall 1). We then conducted a condition (2: Manipulation, Control) by group (2: *Positive*, *Money*) ANOVA for feeling change. Significant effects were followed up with post-hoc t-tests using an alpha level of .05.

3.12 Experiment 6: Results

We examined whether receiving an extrinsic reward (e.g., money) after negative memory recall would be effective for positively updating negative memories similar to positive meaning finding. A condition (2: Manipulation, Control) by group (2: *Positive*, *Money*) ANOVA for feeling change revealed a significant condition by group interaction ($F_{1,54}$= 3.99, p= .05, d= .543). Post-hoc t-tests showed that the *Positive* group had a significantly greater increase in positive emotion on manipulation trials relative to control trials

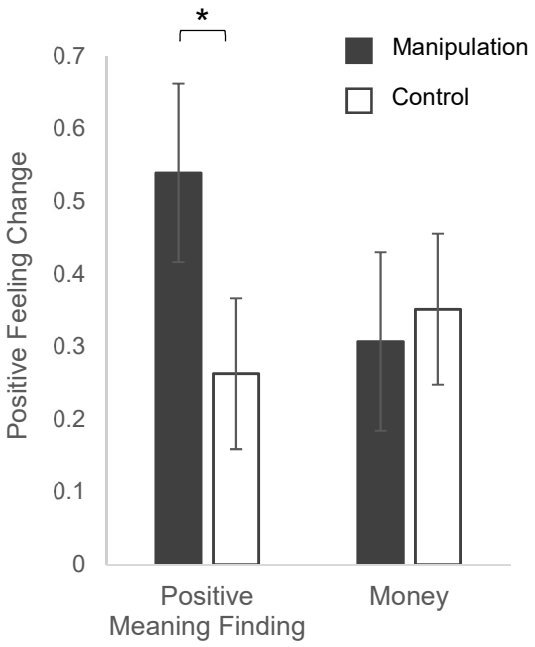


Figure 3.6. Positive meaning finding vs. monetary reward. The Positive group showed an increase in positive emotion for manipulation relative to control trials (natural recall), whereas there was no difference for the Money group, suggesting less successful updating when receiving an extrinsic monetary reward as a potential manipulation for modification. *p<.05; **p<.01

(t_{27}= 2.12, p= .043, d= .465), consistent with Experiments 1-3. In contrast, the *Money* group showed no difference between manipulation and control trials (t_{27}= -0.47, p= .639, d= .072), indicating less successful memory updating (see Fig 3.6).

3.13 Discussion

This research tested a potential strategy for adaptively updating aversive autobiographical memories with positive content: by finding positive meaning in them. Across four experiments, we found converging evidence that positive meaning finding led to enhanced positive emotion and positive memory content at future retrieval. Notably, we replicated these findings four times across different experimental contexts. Our results were consistent regardless of whether people thought about or wrote about their memories, used positive meaning finding in isolation (between-subject) or in conjunction with natural recall (within-subject), and we observed post-retrieval memory changes after both shorter (24h, 1-week) and longer delays (2-months), highlighting the durability and longevity of the effect. We also found evidence suggesting that finding positive meaning in past negative events may leverage the reconsolidation process for memory modification. Further, the self-relevant and intrinsically meaningful context of the strategy may matter, as positive emotion alone (evoked by an extrinsic monetary reward) was less successful in updating negative memories with positive content.

These findings join a burgeoning literature on post-retrieval memory modification. Since reactivated memories can return to a fragile state where they are prone to modification, presenting new information after witnessing or recalling an event can color one's memory of that event (Lee et al., 2017; Nader et al., 2000; Schiller & Phelps, 2011).

There is evidence of this across various memory domains, such as associative memory, whereby undergoing extinction after recalling conditioned fear memories leads to less physiological arousal at future retrieval in humans (Schiller et al., 2010) and reduced freezing behavior in rodents (Nader et al., 2000); procedural memory, whereby a new list of words or methodological sequence can intrude something previously learned (Hupbach et al., 2007; Walker et al., 2003); and episodic memory, whereby listening to others' recollections can change our own memory for the same event (e.g., 9/11) (Coman, Manier, & Hirst, 2009; Coman, Momennejad, Drach, Geana, & Bassett, 2016). This can even occur when the new information is incorrect (e.g., misinformation effect) (Loftus & Palmer, 1974) or is a reconceptualization of what could have been rather than what was (e.g., counterfactual thinking) (De Brigard et al., 2018). A key difference in the present work, however, is that participants internally generate their own positive reinterpretation of an event, rather than receive intervening external information, thus capturing how memory is naturally transformed in everyday life when we choose to think about our negative experiences in a positive light.

Importantly, we examined *how* positively elaborating on negative memories leads to memory modification. Using a paradigm akin to typical reconsolidation studies (Experiment 5), we found that beneficial changes to memory were due to updating of the original memory rather than the creation of a new memory (inspired by the positive elaboration) that competes with the old, as successful modification required prior reactivation. This strategy also did not affect short-term memory, as changes were not observable during the ~6h reconsolidation window, only after (24h), allowing enough time for the reconsolidation process to transpire. Our longitudinal design (Experiment 4) further

demonstrated that beneficial changes to memory content and the emotion it elicits were long-lasting, remaining even after 2-months. This is intriguing because it suggests that the original memory is amended to include positive details, meaning we may be incrementally and adaptively updating our memories each time we positively reinterpret events, leading to less aversive memories in the future. What remains to be tested is if adaptive updating leads to a decreased need for regulating that same negative memory in the future, lessening the cognitive burden of future regulation.

These findings also beg the question of what makes this strategy effective for memory modification? Negative memories might be especially conducive to updating after the introduction of a positive reinterpretation because the incongruence between a positive perspective and the memory's original negative valence may trigger a prediction error. Prediction error signals fuel learning (Schultz, Dayan, & Montague, 1997). They are thus necessary for consolidation—the process by which initially acquired information stabilizes into a memory trace—and later updating of memory after new learning (Nader, 2015). Although we cannot test for the presence of a prediction error directly, data in Experiment 3 match the expected pattern. We observe the largest change in positivity for the strategy with the greatest expectancy violation (positive meaning finding), followed by focusing on neutral aspects and distraction, and the smallest change when focusing on negative aspects.

Given that positive meaning finding is a cognitive regulation strategy, would other regulation strategies similarly update memory? Experiment 3 showed that strategies like distraction or taking a neutral/unemotional stance might have some effect on memory (i.e., a slight elevation in positivity at future retrieval), but they were not as influential as positive meaning finding. This is consistent with the emotion regulation literature. In comparison

to cognitive regulation strategies aimed at reducing negative emotion (e.g., distancing) (Davis, Gross, & Ochsner, 2011), a benefit of positive meaning finding is that it doesn't only dampen negative emotion. It also enhances positive emotion, leading to a greater overall emotion change, which is reflected in subjective reports and physiology (Shiota & Levenson, 2012). Positive reinterpretation even has a differential neural response profile by recruiting regions associated with reward (e.g., ventral striatum, VMPFC; Dore et al., 2016) in addition to regions classically associated with the cognitive control of emotion (DLPFC, VLPFC; Buhle et al., 2014; Ochsner, Silvers, & Buhle, 2012). Focusing on the negative aspects of a negative memory was the least effective in changing memory, which fits with findings on the detrimental effects of over-analyzing or ruminating about negative events.

Similarly, we were interested in whether alternative ways of eliciting positive emotion would have the same beneficial effects on memory. Experiment 6 demonstrated that one such strategy—receiving an extrinsic monetary reward after reactivation—was not as effective for memory updating. The positive intervening information therefore may be most influential when, beyond producing a prediction error via positivity, it is also relevant and intrinsically meaningful to the memory itself. Experiment 3 provides converging evidence as positive elaborations were rated as both more positive and meaningful than negative and neutral elaborations. Previous work fits well with this observation, as conditioned fear memories are lessened when the intervening information is both relevant and meaningful to the memory's context (absence of shock that was previously paired with the memory) (Schiller et al., 2010). In paradigms where the intervening information was beneficial but was unrelated to the memory (e.g., playing a distracting game of Tetris after

watching traumatic videos), it only reduced the recurrence but not emotional quality or content of intrusive memories (James et al., 2015). Future research could explore the precise characteristics (e.g., relevance, meaning) and boundary conditions (e.g., duration) of manipulations that lead to the most effective memory updating.

The present research is not without limitations. First, the positive meaning finding strategy may not work for everyone, as individuals vary in their knowledge and ability to use cognitive regulation strategies (Troy et al., 2013). Across our four experiments, however, 74.4% of memories were successfully regulated (based on self-report and independent raters), and only 3% of participants were excluded from analysis due to substantial difficulty, suggesting this strategy's effectiveness for use in everyday life. With that said, individuals reporting greater anhedonia symptoms were less successful in updating negative memories with positive content. This fits well with prior research demonstrating that individuals with depression, for which anhedonia is a symptom, have difficulty retrieving autobiographical memories in general and positively valenced ones in particular (Young et al., 2013), sustaining positive emotions over time in response to positive stimuli (Heller et al., 2009), and disengaging from negative information (Foland-Ross et al., 2013). Whether positive emotion regulation training in individuals with mood disorders could restore their ability to update negative memories with positive content is an important future inquiry. Second, there may be characteristics about a memory itself that makes it less susceptible to modification. Memories with high emotional arousal, negative valence and/or vividness, such as memories for traumatic events, might be more challenging to update. Although we did not examine such memories, future work could test the efficacy of positive meaning finding for modifying more recurring and intrusive

memories that afflict individuals with stress-related disorders, such as post-traumatic stress disorder (PTSD) (Schwabe et al., 2014).

The desire to change how we remember our past is not new. Finding ways to lessen the deleterious impact of negative autobiographical memories has long captured the attention of researchers and is a prominent objective in therapeutic contexts (Lane, Ryan, Nadel, & Greenberg, 2015). It has even seeped into our pop culture with movies like *Eternal Sunshine of the Spotless Mind* where a painful breakup inspires a couple to erase their memories of each other just to escape it. The present research points to an efficacious strategy for updating negative memories with a more positive perspective. Across four experiments, focusing on the positive aspects of a past negative event led to beneficial changes to long-term memory, such as bolstering positive emotion and bringing positive details of the event to mind at future retrieval, which may promote adaptive psychological wellbeing and resilience to future adversity. Further, this research may have translational potential for individuals with mood or stress-related disorders who face difficulty in reshaping their negative memories into more positive ones.

Chapter 4: Positive Emotion-focused Coping Changes the Neural Representation of Negative Autobiographical Memory

[Experiment 7]

4.1 Introduction

Autobiographical memories have the remarkable ability to bring back emotions tied to the original experience (Bower, 1981). However, remembering negative life events—such as failing an important exam—can trigger the re-experience of negative feelings. One potential way to cope with past adversity is to find positive meaning in it (Shiota & Levenson, 2012). Indeed, positive meaning finding—or focusing on the positive aspects of a negative experience—is central to therapeutic techniques such as cognitive behavioral therapy and is associated with enhanced mental health outcomes (Gross & John, 2003). The ability to flexibly generate or savor positive emotions when feeling down is adaptive for wellbeing (Quoidbach et al., 2010) and cultivating positive emotions can build psychological resources leading to enhanced coping and resilience to future adversity (Fredrickson et al., 2003; Tugade & Fredrickson, 2004). Consistent with this, we observed that enhanced positive emotion via positive reminiscence engaged reward-related neural circuitry (striatum, MPFC) that correlates with individual resilience and improved mood (Speer, Bhanji, & Delgado, 2014), and can even dampen the physiological stress response (i.e., cortisol levels) (Speer & Delgado, 2017).

In the context of regulating negative memories, this leads to an intriguing question: can focusing on the positive aspects of a past negative event adaptively change how we remember that event in the future? Prior work shows that the reactivation of a stored

memory can make it liable and thus prone to updating with newly presented information through a reconsolidation process (Lee et al., 2017; Nader & Hardt, 2009). For instance, a new list of words can intrude a well-learned list (Hupbach et al., 2007) or undergoing extinction after reactivating a fear memory can prevent the return of fear in the future (Schiller et al., 2010). With respect to negative autobiographical memories, we previously found that positive meaning finding leads to enhanced positive emotion and positive memory content at future retrieval, altering how we feel and what we remember even 2-months later, which may promote adaptive psychological wellbeing (Chapter 3). We also found evidence that this positive coping strategy led to the updating of the original negative memory with positive content, leveraging the reconsolidation process, rather than the creation of a new memory that competes with the old. What remains unclear, however, are the neural mechanisms that support this adaptive memory updating.

Prior neuroimaging studies consistently find that dampening negative emotion using cognitive regulation strategies (e.g., reappraisal) modulates prefrontal-limbic circuitry, such as reduced amygdala activity—typically associated with negative affect and emotional salience (Cunningham & Brosch, 2012)—and increased VLPFC and DLPFC activity—typically associated with the cognitive control of emotion (Buhle et al., 2014). Reward-related neural circuits, such as the striatum and MPFC, support positive mood and positive emotion elicited by autobiographical memory in particular (Admon & Pizzagalli, 2015; Speer et al., 2014; Speer & Delgado, 2017). Taken together, positively reinterpreting negatives memories may therefore rely on the synergistic interaction of prefrontal cognitive control and reward-related corticostriatal circuits for adaptive updating of memory. Further, given that positive emotion-focused coping changes how we feel and what we

remember in the future, would updating of such memories be observable across retrievals in neural regions that support memory (e.g. hippocampus) and emotion (e.g., striatum, VMPFC)?

Using multi-session fMRI, we examined the efficacy of positive emotion-focused coping on negative autobiographical memories and the neural mechanisms that promote adaptive memory updating. Specifically, participants underwent an initial fMRI scan while recalling and emotionally rating negative memories from their past (scan #1). They then attempted to modify half of them using positive meaning finding, and only naturally recalled the other half (scan#1). To examine changes to the emotion elicited by such memories and changes in their neural patterns of activity across retrievals, participants returned 24h later to recall and emotionally rate the same memories again (scan #2).

We had three key neural hypotheses. First, we predicted greater activity in corticostriatal and emotion regulatory circuitry (striatum, PFC) during positive meaning finding relative to natural recollection prior to updating (scan #1). We additionally predicted greater engagement of this circuitry for positively reinterpreted memories as a function of increasing positivity during Recall 2 (after memory updating had occurred; scan #2). Second, we used representational similarity analysis (RSA) to examine neural pattern dissimilarity between the two retrieval sessions (Recall 1 and Recall 2) (Visser et al., 2015). Specifically, we predicted greater neural pattern dissimilarity as a function of emotion change across retrievals for positively reinterpreted relative to naturally recalled memories in regions previously implicated in memory (hippocampus), positive affect, and reward (ventral striatum, VMPFC), supporting the notion that this strategy leads to greater changes in the neural representation of memory. Third, we hypothesized that a greater change in

positive emotion across retrievals would be associated with a) greater reward-related and/or emotion regulatory activity during positive meaning finding, and b) greater neural dissimilarity across retrievals.

4.2 Experiment 7: Methods

4.2.1 Participants

40 healthy young adults participated in this multi-session fMRI study. Exclusions included poor performance on the memory recall tasks (difficulty using positive meaning finding, N=4; remembering <50% of memories across sessions, N=1) and motion greater than 3mm in any direction (N=2). The final sample included 33 participants (12 men; M_{age}= 22.8; SD= 4.67). Our target sample size was 35 participants based on prior fMRI studies using similar multivariate analyses (e.g., RSA). Participants gave informed consent in accordance with the Rutgers Institutional Review Board for Protection of Human Subjects and received monetary compensation for participating.

4.2.2 Experimental Design

This was a 4-session study occurring over the course of 2 months. It included an initial behavioral session, two fMRI sessions, and a 2-month behavioral follow-up (see Fig 4.1a for timeline).

Behavioral Session. In the first session, participants completed questionnaires asking about their depressive and anxiety symptoms (Mood and Anxiety Symptom Questionnaire, MASQ; Watson et al., 1995), their ability to savor positive emotions in daily life (Emotion Regulation Profile Revised, ERP-R; Nelis, Quoidbach, Hansenne, &

Mikolajczak, 2011), social and positive coping strategies (COPE Inventory; Carver, 2013), use of cognitive reappraisal and suppression (Emotion Regulation Questionnaire, ERQ; Gross & John, 2003), trait resilience (Connor-Davidson Resiliency Scale, CD-RISC; Connor & Davidson, 2003), and recent life stress (Perceived Stress Scale, PSS; Cohen, Karmarck, & Mermelstein, 1983).

Participants then completed an autobiographical memory questionnaire (AMQ). They were presented with 68 event cues (e.g., Witnessing an accident) that could trigger a specific negative memory from their past (e.g., Car accident in West Village). For each cue, they thought of a negative memory, wrote a brief description (1-2 sentences), provided a date (How long ago did this memory occur?), and made subjective ratings of feeling (How does this make you feel in the present moment? 11-point scale: -5=extremely negative, 0=neutral, 5=extremely positive), intensity (How emotionally intense is this memory? 5-point scale: 1=not intense, 5=extremely intense), vividness (How clearly can you see this memory in your mind? 5-point scale: 1=not vivid; 5=extremely vivid), and social closeness (How close do you feel to the people who were in the memory with you? 1=not close or alone; 5=extremely close). Importantly, participants also created a unique keyphrase (5–10 words) for each memory to provide ease with recollection at future retrievals. The experimenter randomly selected 32 memories from each participant's AMQ that were deemed as negative and occurred at a specific place and time (the minimum criteria for inclusion). Memories were then matched in feeling and intensity ratings across the positive and control condition to ensure similarity at baseline.

Scan 1: Memory Recall 1 and Positive Elaboration. In the second session (1-4 days later), participants completed two tasks while undergoing fMRI scanning. They first

performed a memory recollection task (Recall 1; Fig 4.1b), with the goal of mentally reactivating 32 memories in their mind and obtaining baseline emotion ratings. On each trial, they saw one unique keyphrase for 14s, thought about the memory, and made button presses indicating recall duration. After a short delay (2-4s), they made ratings of feeling and emotional intensity (unrestricted time limit), followed by a 6-10s ITI.

After Recall 1, participants performed a Memory Elaboration task that included the positive manipulation (Fig 4.1c). On each trial they saw one of the 32 unique keyphrases again for 20s. They were asked to positively elaborate (i.e., find positive meaning) on half of them (16 positive trials) and to naturally recall the other half (16 control trials). They made button presses to indicate duration of recall or elaboration, followed by a 2-4s delay. After a positive trial, they were asked: Were you able to think of something positive associated with this memory? (Yes/No). After a control trial, they were asked: Did you think about the specified memory? (Yes/No; unrestricted time limit for ratings). An ITI of 6-10s separated one trial from the next. There were 2 positive blocks and 2 control blocks with 8 trials each. Blocks were presented in counterbalanced order across participants.

Participants rated their current mood via the PANAS before Recall 1 and after the Elaboration task. At the end of Scan 1 participants gave subjective reports of their overall performance on the task. They reported how successful they felt in using the positive elaboration strategy on positive trials and in only thinking about the specified memory on control trials (both 7-point scales: 1=not successful at all; 7=extremely successful), and how difficult it was to switch between the two strategies (7-point scale: 1=not difficult at all; 7=extremely difficult).

Scan 2: Memory Recall 2. In the third session (1-day later), participants underwent their second scan and performed the same memory recall task (Recall 2; 14s recall followed by emotion ratings). Importantly, at the end of each trial they reported whether it was the same memory as the prior session (Yes/No). This ensured that observed changes in memory were due to memory updating rather than participants choosing to think of different memories. This second fMRI session allowed us to measure changes in emotion

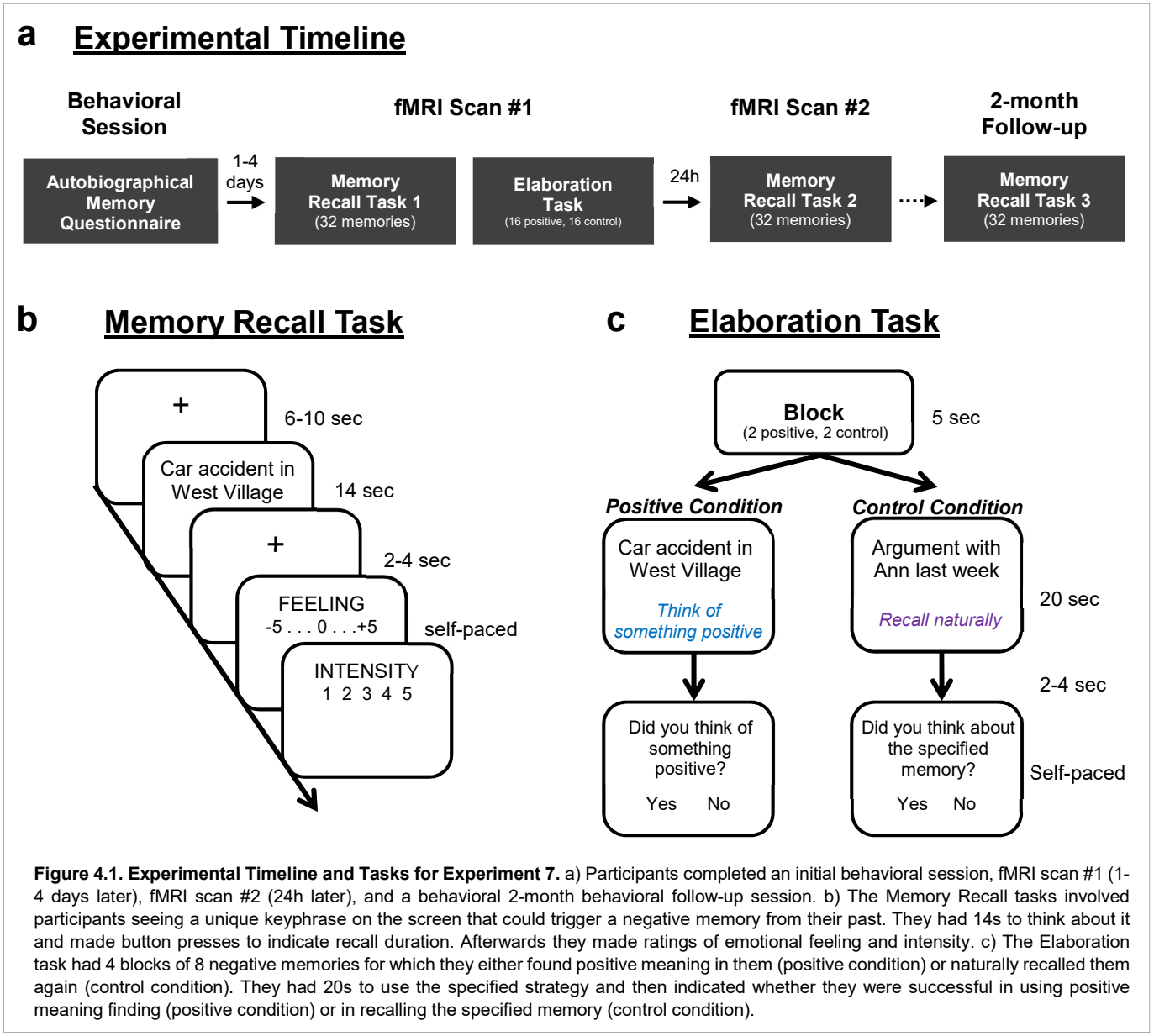


Figure 4.1. Experimental Timeline and Tasks for Experiment 7. a) Participants completed an initial behavioral session, fMRI scan #1 (1-4 days later), fMRI scan #2 (24h later), and a behavioral 2-month behavioral follow-up session. b) The Memory Recall tasks involved participants seeing a unique keyphrase on the screen that could trigger a negative memory from their past. They had 14s to think about it and made button presses to indicate recall duration. Afterwards they made ratings of emotional feeling and intensity. c) The Elaboration task had 4 blocks of 8 negative memories for which they either found positive meaning in them (positive condition) or naturally recalled them again (control condition). They had 20s to use the specified strategy and then indicated whether they were successful in using positive meaning finding (positive condition) or in recalling the specified memory (control condition).

and the neural representation of memories from before (Recall 1) to after positive elaboration (Recall 2).

Participants reported their current mood state before and after the task. At the end of Scan 2 they made additional memory ratings of vividness, social closeness, and frequency of recall (How frequently do you recall this memory in everyday life? 5-point scale: 1=not at all; 5=extremely frequently).

Two Month Behavioral Follow-up. In the fourth session, (2 months later), participants performed the same memory recollection task again (Recall 3; 14s recall followed by emotion ratings). This allowed us to test for longer lasting changes in the memories over time, and served to replicate our longitudinal behavioral study (Experiment 4) (Speer et al., *in prep*).

4.2.3 fMRI Data Acquisition and Preprocessing

A 3T Siemens Magnetom Trio scanner was used for acquisition of T1-weighted MPRAGE structural images (256 x 256 matrix, FOV= 256 mm, 176 1-mm sagittal slices). Functional images were taken in 35 contiguous oblique-axial slices (3x3x3 mm voxels) prescribed parallel to the AC-PC plane with a single shot gradient echo EPI sequence (TR= 2s, TE= 25ms, FOV= 192, flip angle 90, bandwidth= 2232 Hz/Px, echo spacing= 0.51). Data were preprocessed and analyzed using tools from FSL and SPM. Functional images were motion corrected, slice-timing corrected (cubic spline interpolation), spatially smoothed using a Gaussian kernel of 5mm FWHM, temporally smoothed with voxel-wise linear detrending and high-pass filtering of frequencies (three cycles per time course), and spatially normalized to MNI space.

4.2.4 fMRI Data Analysis

Functional data was analyzed using a whole brain random-effects general linear model (GLM). The two Recall tasks and the Elaboration task were modeled using a regressor for memory recall during positive trials, a regressor for memory recall during control trials, and a regressor representing missed trials (i.e., unable to reappraise or not the same memory across sessions). To ensure consistency across participants, we used the mean onset and durations of memory recall and elaboration for the memory and elaboration regressors, respectively (M_{recall}= 3.1, SD=2.1; $M_{elaboration}$=7.4, SD=6.0). Parametric models additionally included a parametric regressor for the degree of feeling rating change across retrievals (Recall2 – Recall1) during memory recall (orthogonalized with respect to the memory regressors) or during elaboration (orthogonalized with respect to the elaboration regressors).

For all analyses, regressors were convolved with a canonical double-gamma hemodynamic response function and twenty-four regressors for motion parameters were included in the model. We additionally performed a motion scrubbing procedure to remove noise in the signal. To correct for multiple comparisons, we used a non-parametric permutation test (5000 iterations) to obtain an alpha<.05.

4.2.5 Representational Similarity Analysis (RSA)

We performed representational similarity analyses (RSA) to examine neural pattern similarity between the two retrieval sessions (Recall 1 and Recall 2) as a function of condition (positive, control). RSA requires the construction of representational dissimilarity matrices (RDMs), which summarize the pairwise dissimilarities between

stimuli (Kriegeskorte, Mur, & Bandettini, 2008). In our case, we were interested in comparing neural patterns in Recall 1 to Recall 2 in ROIs previously implicated in positive emotion and reward (ventral striatum, VMPFC) and memory (hippocampus). As an additional exploratory analysis, we also tested other ROIs associated with emotion and memory, such as the amygdala and caudate.

To conduct RSA, we first extracted the multivariate neural pattern in each ROI for each memory in both recall tasks for each participant. We then calculated the correlation distance between the two neural patterns of activity for Recall 1 and Recall 2 of the same memory in a particular ROI, which made up the RDM for brain space. We then constructed a similar RDM for feature space, which included the corresponding emotion change values for each pairwise comparison. To test our hypothesis that positive meaning finding leads to greater neural dissimilarity (than natural recall) across retrieval sessions, we computed RDMs separately for positive and control trials. Then, we calculated the spearman rho correlation between RDMs for brain space (in a particular ROI) with RDMs for feature space (change in feeling rating across retrievals) for each participant and for each condition, separately. Finally, we compared the mean correlation coefficients across conditions (at the group level) using a paired t-test (non-parametric permutation test with 5000 iterations).

In a separate analysis focusing on the positive condition, we also examined whether neural responses during elaboration predict neural pattern dissimilarity across retrievals. We tested this in two ways: 1) correlations between mean neural activity during elaboration and neural RDMs across retrievals, and 2) a parametric regression of the degree of neural dissimilarity on a trial-by-trial basis during elaboration.

4.3 Experiment 7: Behavioral Results

4.3.1 Changes in emotion across memory retrievals

We examined the degree to which memories changed in their emotional feeling ratings across retrievals from before (Recall 1) to 24h after positive elaboration (Recall 2). In line with our prediction, positively reinterpreted memories elicited enhanced positive emotion at future retrieval (24h later) as compared to memories that were naturally recalled (t_{32}= 5.38, p< .001, d= 0.89; Fig 4.2a). Importantly, memories in these two conditions did not differ in baseline ratings of feeling, intensity, vividness, frequency of recall or age (all p>.20), indicating that these factors cannot account for our findings. They also did not differ in baseline onset or recall duration, suggesting that neither condition had memories that were easier or more difficult to remember.

To test the longevity of the effect, we asked participants to return 2-months later to recall these same memories again in a behavioral session. Almost two-thirds of participants returned (n=19).

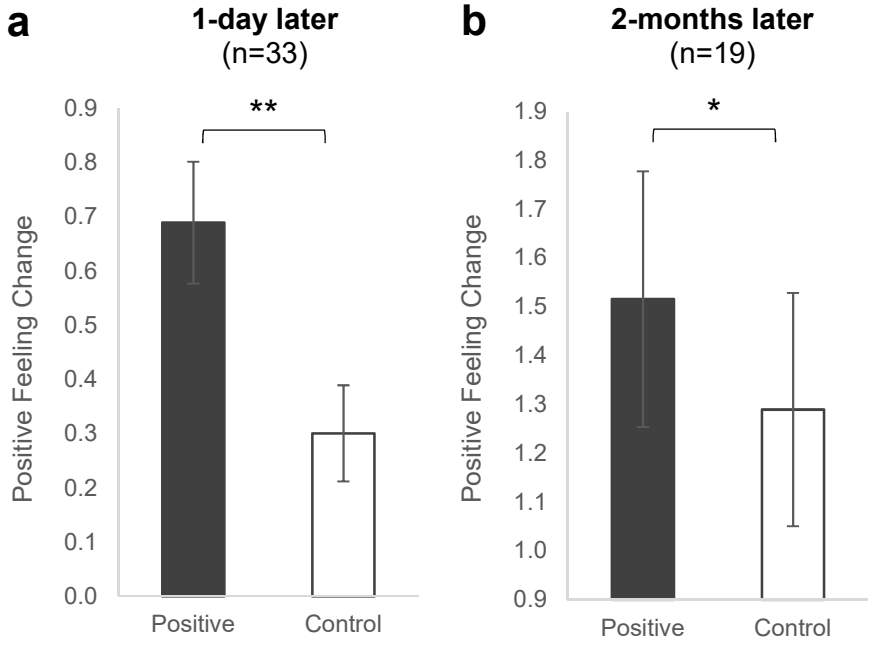


Figure 4.2. Change in positive emotion over time. a) Using positive meaning finding after initial negative memory recall (fMRI scan #1) led to increased positive emotion at future retrieval 1-day later (fMRI scan #2), as compared to natural recollection after initial recall. b) For the subsample (n=19) who returned for the behavioral follow-up, this effect was still present 2-months later. *p<.05; **p<.01

Interestingly, memories that had been positively reinterpreted 2-months earlier still showed a greater increase in positivity at retrieval than memories that were not (t_{18}= 3.54, p= .002, d= 0.84; Fig 4.2b), indicating that positive emotion-focused coping did in fact have a long-lasting impact on memory.

4.4 fMRI Results

4.4.1 Elaboration Task: Neural responses to positive meaning finding vs. natural recollection

We first performed whole-brain analyses contrasting memories that were positively reinterpreted (positive trials) relative to naturally recalled memories (control trials) in the Elaboration Task. This revealed activation consistent with prior neuroimaging studies examining positive reappraisal in particular (Dore et al., 2016) and cognitive reappraisal more generally (Buhle et al., 2014; Wager et al., 2008). Specially, when positively elaborating on negative memories, there was greater activity in regions previously implicated in reward, such as bilateral ventral striatum, bilateral caudate, and ventromedial prefrontal cortex (VMPFC), as well as regions previously implicated in the cognitive control of emotion, such as left ventrolateral prefrontal cortex (VLPFC), left dorsolateral prefrontal cortex (DLPFC) and dorsomedial prefrontal cortex (DMPFC, see Fig. 4.3a).

It is important to note that participants only reported emotion ratings during the two retrievals (Recall 1, Recall 2) and not during the Elaboration task. Our reasoning was that participants' subjective ratings after reinterpretation would occur during the modification period and therefore could potentially become embedded in their memory, which could confound their emotion rating at future retrieval (24h later). To examine the efficacy of positive elaboration, in lieu of these ratings, we tested whether the strength of one's behavioral effect (feeling change across retrievals) was associated with greater neural activity in reward-related and cognitive control-related regions during positive elaboration.

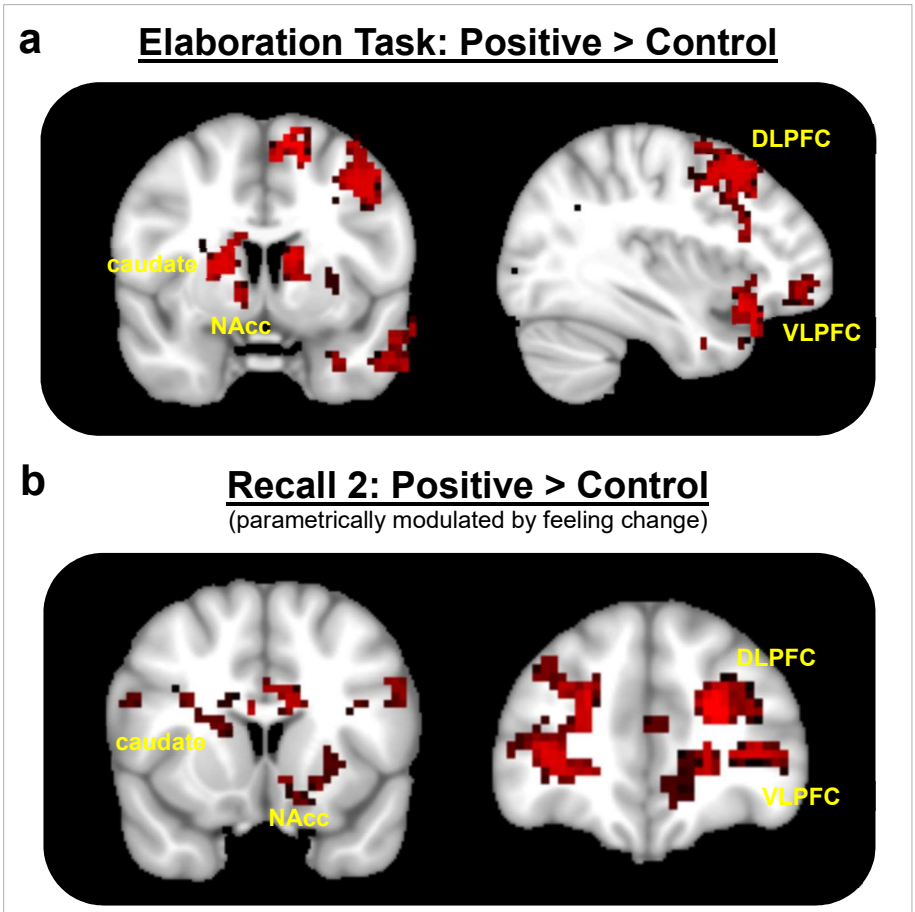


Figure 4.3. Neural responses to positive meaning finding relative to natural recall. a) Positive meaning finding relative to natural recall during the Elaboration task engaged regions previously associated with subjective value/reward (caudate, Nacc) and the cognitive control of emotion (DLPFC, VLPFC; p<.05 corrected). B) Interestingly, the same analysis parametrically modulated by positive emotion on a trial-by-trial basis during future retrieval (Recall 2 task) engaged a similar neural circuitry (p<.05 corrected).

Consistent with this prediction, a greater increase in positivity across retrievals (Recall2 – Recall1) was associated with greater activity in the DLPFC (r_{32}= .450, p= .009) and VLPFC (r_{32}= .354, p= .043) during positive elaboration, suggesting that engagement of this neural circuitry was associated with more successful emotion change over time.

4.4.2 Memory Recall 1 & 2: Neural responses to positive meaning finding vs. natural recollection

We also performed a whole-brain positive > control contrast during Recall 1 and Recall 2, which yielded no significant activations. However, our key analysis was to examine neural activity tracking changes in emotion at the second retrieval (24h after modification occurred). Therefore, we performed a positive > control contrast with the additional inclusion of parametric regressors for feeling change (Recall2 – Recall1) on a trial-by-trial basis for both positive and control trials during Recall 2. This parametric contrast during Recall 2 indexing positive emotion revealed a very similar activation map to the positive > control contrast during the Elaboration task. That is, we found greater activity for positively reinterpreted memories relative to naturally recalled memories as a function of increasing positivity in regions associated with reward and positive affect (ventral striatum, caudate, VMPFC) as well as emotion regulation (VLPFC, DLPFC, DMPFC, see Fig. 4.3b). This suggests that negative memories updated with positive content may re-engage the same corticostriatal circuitry they previously engaged during positive elaboration.

4.4.3 Neural pattern similarity across memory retrievals

One intriguing hypothesis was whether positively elaborating on negative memories would lead to changes in the neural representation of those memories over time. Specifically, we examined whether memories that underwent positive meaning finding during the Elaboration task (i.e., positive trials) would have greater *dissimilarity* in their neural activation patterns across retrievals (from before modification to 24hr later), in comparison to memories that were naturally recalled, and thus not modified during the Elaboration task (i.e., control trials). Using RSA, we first tested this hypothesis in regions previously associated with positive affect (NAcc, VMPFC) and memory retrieval (hippocampus). This analysis involved extracting multivariate activation patterns from each ROI, defined by a neurosynth parcellation, for each condition (positive, control) during each retrieval (Recall 1, Recall 2). Then, we computed the correlation distance across retrievals for a particular memory, and used these values to create RDMs for each condition for each participant. Using the same steps, we created similar RDMs for emotion change across retrievals, and correlated the neural RDM with the corresponding emotion change RDM for each condition and each participant (see Fig 4.4a). We then compared the mean correlations between conditions (positive, control) at the group level. Consistent with our prediction, a paired-samples t-test revealed greater neural dissimilarity across retrievals as a function of increasing positivity in the positive condition, relative to the control condition, in both the hippocampus (t_{31}= 2.36, p= .022, d= 0.38) and ventral striatum (t_{31}= 2.42, p= .019, d= 0.39, Fig 4.4b), but not the VMPFC.

As an exploratory analysis, we then tested this hypothesis in other regions broadly associated with emotion and emotional memory, such as the amygdala and caudate, but neither of these ROIs showed a relationship between neural pattern dissimilarity and emotion change across retrievals for positive relative to control trials.

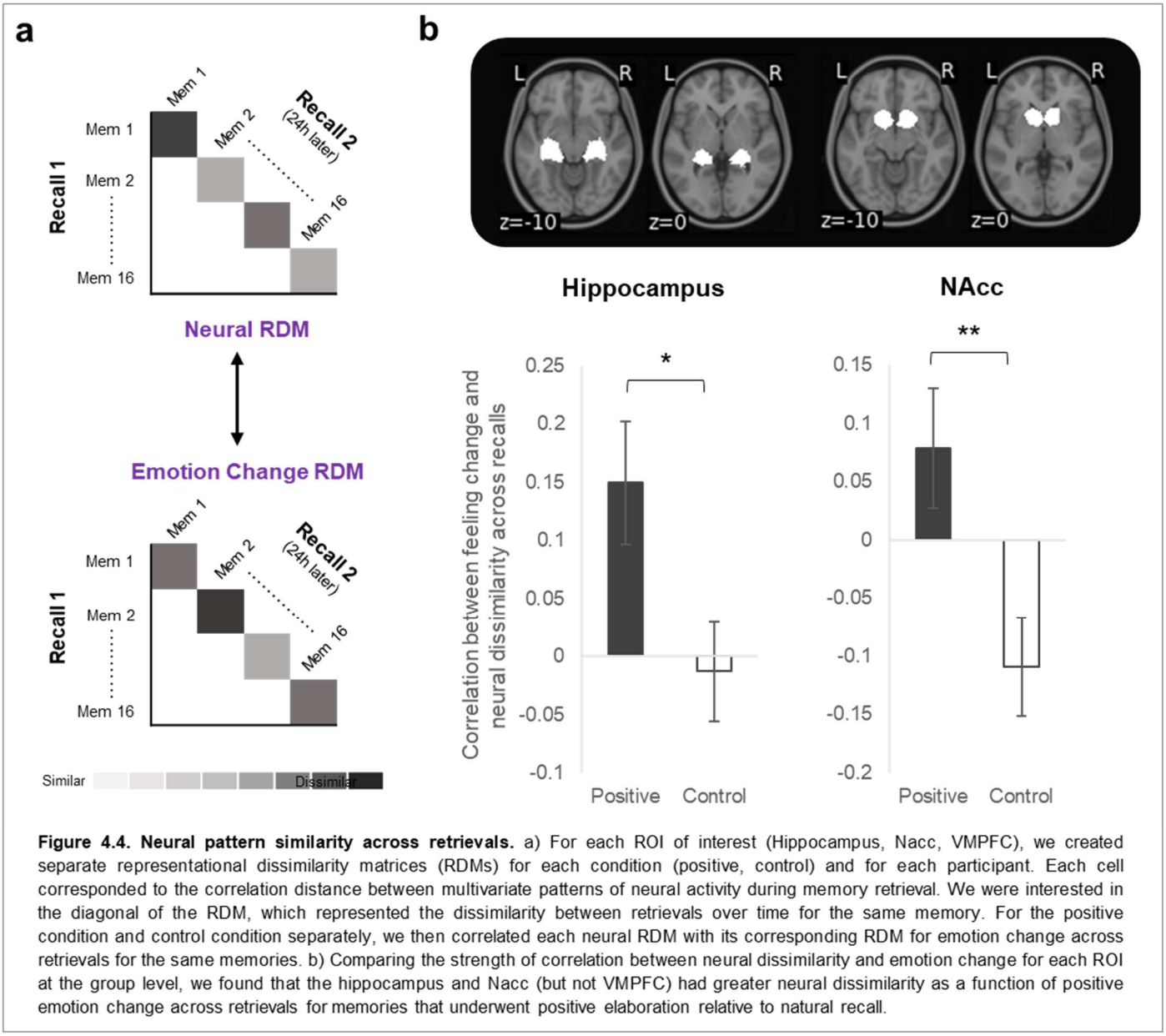


Figure 4.4. Neural pattern similarity across retrievals. a) For each ROI of interest (Hippocampus, Nacc, VMPFC), we created separate representational dissimilarity matrices (RDMs) for each condition (positive, control) and for each participant. Each cell corresponded to the correlation distance between multivariate patterns of neural activity during memory retrieval. We were interested in the diagonal of the RDM, which represented the dissimilarity between retrievals over time for the same memory. For the positive condition and control condition separately, we then correlated each neural RDM with its corresponding RDM for emotion change across retrievals for the same memories. b) Comparing the strength of correlation between neural dissimilarity and emotion change for each ROI at the group level, we found that the hippocampus and Nacc (but not VMPFC) had greater neural dissimilarity as a function of positive emotion change across retrievals for memories that underwent positive elaboration relative to natural recall.

4.4.4 Relationship between neural activity during positive elaboration and future memory change

We predicted that neural activity when using positive meaning finding during the Elaboration task might be related to future changes in memory. Therefore, we conducted a whole-brain parametric regression analysis for memories in the positive condition during the Elaboration task weighting each memory by its dissimilarity across retrievals within the hippocampus and the ventral striatum, separately (i.e., correlation distance from RSA analysis). This analysis would yield neural activity associated with greater neural dissimilarity from before to after modification. However, neither of these contrasts revealed activity that survived correction. In addition to examining across the whole-brain, we tested this hypothesis with more targeted analyses. Specifically, we tested for correlation between neural activity during positive elaboration trials in regions associated with reward (striatum, VMPFC) and cognitive control (VLPFC, DLPFC) and neural pattern dissimilarity in the hippocampus and NAcc on a trial-by-trial basis, separately. However, these analyses showed no significant relationships.

4.4.5 Individual differences related to positive elaboration and future memory change

We were also interested in whether protective factors, such as resilience to stress and ability to savor positive emotions in daily life, might be related to a) neural responses during positive emotion elaboration and b) changes in future memory. We first tested whether these traits were related to greater neural responses in regions associated with positive emotion (striatum, VMPFC) and cognitive regulation (VLPFC, DLPFC) during positive meaning finding (in the Elaboration task). Interestingly, greater savoring ability,

as measured by the ERP-Revised (Emotion Regulation Profile-Revised; Nelis et al., 2011), was related to greater activity in the caudate during positive meaning finding (r_{32}= .535, p= .001; Fig 4.5a).

We then tested whether these traits were related to future memory change, in terms of feeling change, hippocampal dissimilarity or ventral striatum dissimilarity—both of which significantly differed across the positive and control conditions. Greater savoring ability was associated with greater hippocampal dissimilarity across retrievals (r_{32}= .447, p= .009; Fig 4.5b). That is, one's natural propensity to savor positive emotions in everyday life is associated with both greater neural responses in regions previously implicated in reward or value (i.e., caudate) when positively reinterpreting negative memories, as well as greater changes in the neural representation of memory in the hippocampus over time. There was no relationship between these variables and individual resiliency scores.

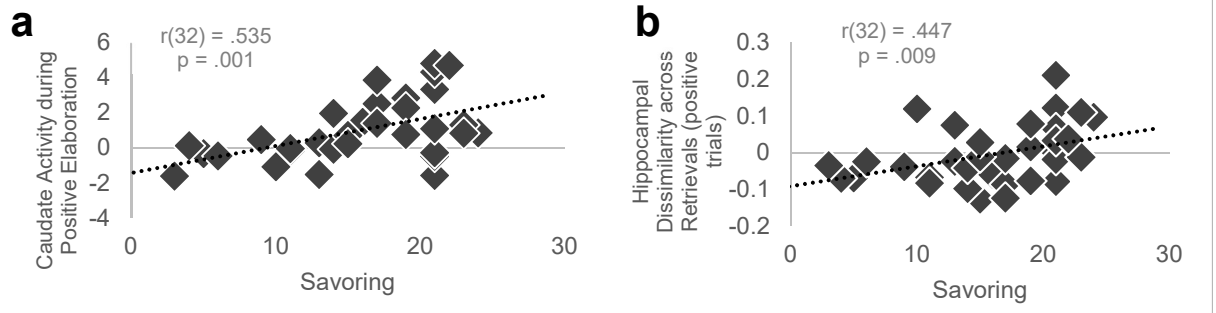


Figure 4.5. Individual differences in savoring relates to neural activity associated with positive meaning finding. A greater ability to savor positive emotions in everyday life was associated with a) greater reward-related activity (caudate) during positive elaboration in fMRI scan #1 and b) greater neural pattern dissimilarity in the hippocampus across retrievals, suggesting greater change to the neural representation of memory after using positive meaning finding.

4.5 Discussion

We sought to characterize the neural mechanisms of negative memory modification via positive meaning finding. Using multi-session fMRI, we found novel evidence that positively reinterpreted memories have greater hippocampal and striatal pattern dissimilarity (relative to naturally recalled memories) as a function of emotion change across retrievals. That is, memories that became more positive after using positive emotion-focused coping also had a greater change in their multivariate activation pattern across retrievals in regions previously associated with memory and reward. Increases in positive emotion at future retrieval were long-lasting, as they remained even after 2-months, replicating our previous work (Chapter 3). Prefrontal cognitive control regions (DLPFC and VLPFC) along with reward-related circuitry (striatum, VMPFC) supported modifications to memory induced by positive meaning finding and tracked the degree of emotion change at future retrieval. Interestingly, these findings were most pronounced in individuals who have a greater propensity to savor positive emotions in everyday life, suggesting a benefit to wellbeing for using positive emotion regulation to cope with maladaptive memories.

Our finding that positive reinterpretation led to modifications in an autobiographical memory's neural representation in the hippocampus and striatum extend our knowledge of how memory is represented in the brain across time. Previous work demonstrated that a better match in multivariate neural activation patterns (in posterior visual regions) between encoding of a visual image and later retrieval was associated with better memory performance, especially for emotional stimuli (Ritchey, Wing, Labar, & Cabeza, 2012). There was similar evidence for repetitions across retrievals of the same

image (e.g., faces; Xue et al., 2010), consistent with the widely held notion that repetition of information tends to improve test performance. Building on this work, we found that when intentionally modifying a negative memory by thinking about it in a positive light, the change in emotion and content that occurs (Speer et al., *in prep*) is also reflected in the brain. Modified memories show greater Recall1-Recall2 dissimilarity in their hippocampal and striatal activation patterns than when simply recalling a memory naturally without modification, and this dissimilarity corresponds with the strength of positive emotion increase on a memory-by-memory basis. Such changes in the hippocampus and the striatum fit well with their role in memory processing (Goldfarb, Chun, & Phelps, 2016; Lisman et al., 2017). Indeed, the hippocampus—part of the medial temporal lobe—is largely responsible for the consolidation of information (after encoding) into a stable memory trace that is available at future retrievals (Tompary & Davachi, 2017). Although the striatum is primarily linked to value, positive affect and motivational states (Delgado, 2007), the striatum is also associated with memory retrieval success (Schwarze, Bingel, Badre, & Sommer, 2013; Scimeca & Badre, 2012).

We also explored the neural mechanisms underlying such beneficial future changes to memory. While using positive meaning finding relative to natural recall (prior to updating), individuals engaged prefrontal regions (VLPFC, DLPFC) commonly associated with the cognitive control of emotion, which is consistent with the emotion regulation literature at large (Kross et al., 2009; Morawetz et al., 2016; Ochsner et al., 2012), and specifically for cognitive strategies involving reinterpretation (Buhle et al., 2014; McRae, Gross, et al., 2012). The additional engagement of value-related circuitry (striatum, VMPFC) is consistent with a previous study explicitly examining positive emotion-focused

reinterpretation (looking on the bright side) relative to minimizing reinterpretation, such as thinking about something negative in neutral or unemotional terms (Dore et al., 2016). DLPFC and VLPFC activity also correlated with greater positive emotion change across retrievals, which may index emotion regulation success. Intriguingly, the same neural circuitry engaged during positive meaning finding—prefrontal cognitive control and reward-related regions—also tracked increased positive emotion during future retrieval of updated memories. This provides complementary support for research investigating the long-term effects of emotion regulation, whereby viewing previously regulated images led to similar reductions in amygdala response as during the original regulation period (Denny, Inhoff, Zerubavel, Davachi, & Ochsner, 2015).

There are some limitations about this study that merit discussion. First, because we had targeted hypotheses about specific regions that might show changes in neural pattern activity across time, our RSA analyses were restricted to ROIs. While this helped us specifically test regions linked to memory and reward, it did not allow for us to test whether neural patterns change more broadly across the brain. Second, other qualities of a memory, such as their vividness and richness, may change as a function of using emotion regulation strategies, and thus may correlate with neural pattern similarity across retrievals as well. Future work could take a more multivariate approach to test the combined and also unique roles of multiple aspects of memory and how they contribute to memory updating. Third, given time constraints and motion-restriction in the scanner, participants were only able to use mental recall rather than written recall, meaning we were only able to measure changes in emotion but not changes in memory content. Although we surmise that memories changed in both emotion and memory content in the present study, especially given our

prior behavioral findings (Chapter 3), future research could extend this work to examine the neural mechanisms tracking changes in memory content over time.

The discovery that a well-established memory is not set in stone and can be adaptively modified with new content has meaningful clinical implications. We found that individuals who naturally savor positive emotions in daily life reaped greater benefits, in terms of greater reward-related activity when using positive meaning finding and greater hippocampal pattern dissimilarity across retrievals correlating with greater positive emotion. A better understanding of memory updating via positivity could help us identify potential deficits in neural circuitry present in those who fail to update their memories on a long-term scale. Individuals with depression, for instance, have difficulty sustaining neural responses in the striatum in response to positive stimuli (Heller et al., 2009), and have overgeneral autobiographical memories leading to deficits in memory recall, particularly for positive life events (Young et al., 2013). Extensions of the present study could therefore help us identify neural deficits correlating with depressive symptomology, which could inform clinical treatments.

Overall, this research showed that positive meaning finding can effectively regulate emotion evoked by negative memories, this strategy can serve as a way to update memories with a positive perspective, and this is reliant upon prefrontal cognitive control and reward-related neural circuitry.

Chapter 5: General Discussion

5.1 Summary & Implications of Dissertation Experiments

The overarching goal of this dissertation was to examine whether positive emotion-focused coping can effectively mitigate negative affective states. We examined this in the context of (a) coping with negative affect occurring in the present moment (e.g., experiencing acute stress) by using positive reminiscence and (b) coping with negative affect stemming from past adversity (e.g., remembering negative memories) by using positive meaning finding.

5.1.1 The stress-buffering nature of positive reminiscence

In Aim 1 of this dissertation, we examined an important question regarding the neural correlates of emotion regulation, stress and wellbeing: Can we use positive emotions as a way to cope with the negative feelings associated with stress? Specifically, across two studies, we examined whether recalling autobiographical memories that have a positive content—i.e., remembering the good times—can buffer the hypothalamic-pituitary-adrenal axis stress response, such as reducing stress hormone levels (i.e., cortisol) and negative affect. We first tested this behaviorally (N=134) and then using fMRI (N=43). Participants underwent an acute stressor or control task followed by autobiographical memory recollection (of only positive or neutral valence). In both studies, our novel findings revealed that recalling positive, but not neutral, memories resulted in a dampened cortisol rise and reduced negative affect after stress exposure—a noteworthy finding given its replicability across two samples (Speer and Delgado, 2017). Our fMRI data further showed that positive reminiscence under stress engaged regions previously implicated in emotion

regulation (DLPFC, VLPFC) and reward-processing (striatum, MPFC). Our results highlight the restorative and protective function of self-generated positive emotions via memory recall in the face of stress.

Acute stress can have powerfully detrimental effects on one's mental and physical wellbeing, such as impairing decision-making and working memory in addition to causing emotional distress. Unfortunately, it is under such stressful circumstances that cognitive emotion regulation strategies (e.g., reappraisal) are rendered ineffective (Raio et al., 2013), suggesting a critical need for alternative ways to mitigate stress. For the first time, we demonstrate that enhancing positive emotions via memory recall can actually restore stress-induced deficits, which may occur through engagement of the prefrontal cognitive control regions. The strategy of positive reminiscence is unique in that it allows us to capitalize on the positive emotions we feel when recalling the past, which is something we already do naturally. Thus, it does not require reinterpretation or necessarily a cue, in contrast to cognitive strategies that aim to diminish the emotional impact of a current stressor (Gross, 2002), which may only be effective in certain contexts or for particular individuals (Troy et al., 2010). Overall, these findings provide proof-of-concept evidence of the effectiveness of this strategy, conveying the simple, yet powerful idea that savoring the past may be an adaptive tool for combating life's troubles. Importantly, this research combines various methodologies (cortisol, galvanic skin response, subjective reports and fMRI) and thus may have interdisciplinary appeal and potential relevance to researchers and clinicians studying positive affect, emotion regulation, memory, stress, and resiliency.

5.1.2 Finding positive meaning in past negative events beneficially changes memory

In Aim 2 and 3 of this dissertation, we examined the efficacy of positive emotion-focused coping for dealing with negative autobiographical memories. Vividly recalling negative experiences from the past can retrigger those same painful feelings all over again (e.g., witnessing a car accident; Bower, 1981). One potential way to alter how we feel about past adversity is to find positive meaning in it. Specifically, we asked whether focusing on the positive aspects (e.g., learned better study skills) of a past negative memory (e.g., bad grade on an exam) can adaptively update that memory with positive content, thus changing how we feel (emotional feelings induced by the memory) and what we remember (content of the memory) in the future.

We first tested this across 4 behavioral studies (N=321). In Study 3, participants reactivated 12 negative memories. They wrote descriptions, made emotion ratings, and then elaborated on them by either focusing on each memory's positive, negative, or neutral aspects, or performed a distracting task (4 different groups). To test for changes over time, they recalled their memories again 1-week later. Notably, only the positive group had enhanced positive emotion at future retrieval. Individuals with the greatest change in positive content also had the greatest positive emotion increase. Critically, we replicated these findings across all 4 studies. Adaptive updates to positive emotion and memory content were long-lasting, remaining even after 2 months (Study 4), highlighting the durability and longevity of the effect. Positive meaning finding only led to updates after a reminder and a 24h, but not a 1h delay, consistent with a reconsolidation account (Study 5). Finally, it was also more effective than receiving a monetary reward after retrieval

(Study 6; Chapter 3), suggesting that the intrinsically meaningful context of the strategy may matter for updating.

We then sought to characterize the neural mechanisms underlying this phenomenon using fMRI (N=33; Study 7). Notably, neural circuits previously implicated in reward processing (striatum, VMPFC) and emotion regulation (DLPFC, VLPFC) tracked the degree of positivity change at future retrieval. We then tested the critical question of whether updates to the memory itself occurred. Using representational similarity analysis, positively reinterpreted memories had greater neural pattern dissimilarity across retrievals in regions previously implicated in reward (striatum) and memory (hippocampus), suggesting a greater change to the neural representation of memory after using positive meaning finding (Chapter 4).

Together, across 5 experiments using different experimental contexts, we found that finding positive meaning in past negative events can successfully update aversive memories with positive content—a finding that was shown at both shorter (24h, 1-week) and longer (2-month) delays, and is observed in subjective reports of emotion, written memory content at the time of recollection, and in the neural representation of memory while undergoing fMRI scanning. This exciting work highlights a potentially efficacious strategy for coping with persistent maladaptive memories via positive emotion. These findings are particularly novel as they show for the first time that we can make long-lasting changes to our own unique recollections of past negative events by using a simple positive cognitive intervention, capturing a naturally-occurring phenomenon in everyday life: when we choose to think about or talk about past negative events in a more positive light. Given the long-term beneficial effects this strategy has on both the emotion elicited by memory

and the details we remember about the past event, positive meaning finding may promote positive wellbeing and resilience to future adversity. It may also have translational potential for individuals with mood disorders or post-traumatic stress disorder who face difficulty in reshaping their negative memories into more positive ones.

5.2 Positive Emotion-focused Coping for Emotion Regulation and Building Resilience to Future Adversity

The ability to regulate emotion under stressful circumstances is a crucial component of resilient coping and healthy psychological functioning. Our 7 experiments provide converging evidence that positive emotion-focused strategies are beneficial for coping with negative affective states. Intriguingly, both strategies we tested—positive reminiscence and positive meaning finding—engaged neural circuitries previously associated with reward and positive affect (striatum, VMPFC) and the cognitive control of emotion (DLPFC, VLPFC) to dampen negative emotions elicited by experiencing an acute stressor or retriggered by remembering past negative events. What is it about positive emotion-focused coping that makes it particularly adept at counteracting adversity (whether occurring in the present or from the past)?

Experiencing stress or adversity elicits negative emotions and restricts one's focus, making problem-solving more challenging. Conversely, strategies that bolster positive emotions broaden one's perspective, inspiring curiosity, creativity, and pleasant thoughts and memories (Conway, Tugade, Catalino, & Fredrickson, 2012), that may even give rise to the positive reinterpretation of events (e.g., positive meaning finding, reappraisal). Greater frequency of positive emotions is also associated with increased attention to

positive stimuli and feelings of social interconnectedness. The ability to internally generate positivity may be especially adaptive under stress because stressful situations often lack positive cues, and the downstream benefits of positivity—broadened cognition and enhanced social connection—are exactly what makes it easier to deal with stress (Tugade & Fredrickson, 2006). Positive emotions can also speed affective and physiological (cardiovascular) recovery from negative emotions, which is a key aspect of resilience (Fredrickson & Levenson, 1998).

Beyond the immediate effects of positivity on stress, the cumulative experience of savoring and prolonging positive emotions over time is thought to build psychosocial resources for resilient coping (Conway et al., 2012), thus making it more likely to notice rewarding aspects in the environment and think positively in the future. It has been suggested that positive emotions are not just the consequence of more adaptive coping styles and better psychological outcomes (Tugade & Fredrickson, 2004), but that they may also causally influence resilient coping. In longitudinal studies, caretakers who used positive meaning finding more frequently reported greater positive mood both before and after the death of a loved one (Mokowitz et al., 1996). More generally, the ability to increase positive feelings in response to a stressor is positively correlated with post-stressor mood and wellbeing (Troy et al., 2010), which we found in the present research as well (Chapter 2; Speer & Delgado, 2017), and interventions aimed at increasing positive feelings are associated with more successful recovery from depression (McMakin, Siegle, & Shirk, 2011).

One outstanding question is what factors contribute to individual differences in savoring and resilience? Some individuals may have a natural propensity for bolstering

positive feelings, which may be evidenced in greater engagement of reward circuits, such as greater striatal activity during reappraisal (McRae, Ochsner, Mauss, Gabrieli, & Gross, 2008) or in response to rewards under stress (Nikolova, Bogdan, Brigidi, & Hariri, 2012), or more flexible signals in the VMPFC associated with adaptive stress coping strategies (Sinha, Lacadie, Constable, & Seo, 2016). In support of this idea, individuals who had the greatest striatal activity during positive reminiscence showed the greatest benefit to their mood afterwards, and enhanced striatal activity was further correlated with greater self-reported resilience (Speer et al., 2014). In the present research (Experiment 1), we also found that resiliency mediated the relationship between positive emotion during recall and positive mood afterwards, despite stress exposure, providing additional evidence that resilient individuals may benefit more from using savoring strategies.

Another possibility is that using reactive savoring strategies (e.g. positive meaning finding) has a stronger influence on resilience than proactive savoring strategies (e.g., being present-focused; positive reminiscence), because they give more direct practice in infusing negative events with positive meaning, which may inspire a greater sense of purpose or eudaimonic wellbeing (Ryan & Deci, 2001). For instance, individuals who reported the highest levels of eudaimonic wellbeing exhibited greater sustained engagement of the striatum and DLPFC to positive images and had the lowest daily cortisol output—a marker of stress hormone levels (Heller, van Reekum, et al., 2013). As an extension to prior work, in Experiment 7, we found that individuals with greater savoring ability had greater reward-related (striatal) activity when using positive meaning finding and also had greater changes in hippocampal activation patterns across retrievals, suggesting more significant updating of memory.

By contrast, mood disorders are characterized by emotion dysregulation and lower resilience and psychological wellbeing. Individuals afflicted with depression report lower levels of positive emotion, engage in less positive social sharing (Hames, Hagan, & Joiner, 2013), and exhibit diminished behavioral and neural (striatal) sensitivity to rewards (Pizzagalli, Jahn, & O'Shea, 2005; Pizzagalli et al., 2009). Importantly, depressed individuals also have difficulty sustaining striatal activity and positive emotions in response to positive stimuli (Heller et al., 2009), which is further associated with reduced striatal-PFC connectivity, suggesting that diminished ability to sustain positive emotions in depression may be due to deficits in recruiting the PFC during cognitive regulation. Consistent with this, depressed individuals who can easily inhibit positive emotion (enhanced PFC activity) show the least improvement in anhedonia symptoms after antidepressant treatment (Light et al., 2011), whereas those with the greatest increase in striatal-PFC connectivity after treatment show the greatest improvement in positive affect (Heller, Johnstone, et al., 2013).

Similarly, in Experiment 4, we found that individuals with greater anhedonic symptoms had smaller increases in positive content across memory retrievals, suggesting greater difficulty in updating their memories, as positive content did not 'stick' over time. Our neuroimaging analyses (Experiment 7) further indicated that finding positive meaning in past negative memories engaged the same neural circuitry compromised in depression—emotion regulatory (PFC) and reward-related circuits (striatum). Although our fMRI sample was not large enough to test meaningful individual differences, future work could explore the neural circuitry of positive-emotion regulation deficits in depression/anhedonia, leading to unsuccessful updating of memory. This in turn could help

inform better clinical treatments, especially for counteracting rumination of past negative events.

In all, these findings suggest that increased connectivity between reward-related and prefrontal cognitive control regions may be critical for savoring or prolonging positive affect over time, resulting in lower levels of stress and greater resilience to promote better wellbeing. Interventions aimed at increasing both the frequency and duration of positive emotion and facilitating social connection may be especially helpful for mood disorders, such as depression. Prior work has additionally shown that capitalizing on a diverse set of savoring strategies is more beneficial than using a select few (Quoidbach et al., 2010). How different forms of savoring (proactive vs. reactive) and which specific positive emotion-focused coping strategies (uniquely or together) contribute to resilient coping will be an important future inquiry.

5.3 Limitations & Future Directions

Beyond the limitations and alternate interpretations described in each preceding chapter, there are additional limitations about these collective experiments as a whole. For instance, we examined the effects of positive emotion-focused coping on two kinds of negative affective states: acute stress responses and negative memory retrieval. However, because both of these states trigger only moderate levels of negative affect, our results cannot speak to whether these positive coping strategies would be effective with higher levels or more persistent forms of negative affect, such as recalling traumatic experiences or chronic stress exposure. We did observe higher stress levels (in terms of overall stress hormone response; cortisol) in our neuroimaging stress study (Experiment 2) as compared

to our behavioral version (Experiment 1), given that the MRI environment can exacerbate stress, which may provide some insight. Here, positive memories still dampened cortisol responses, suggesting that they may be effective for higher stress levels. In Experiments 3-7, we only tested the efficacy of positive meaning finding on negative memories that ranged from slightly to moderately negative, but not traumatic memories that may lead to more persistent rumination in everyday life. Thus, future work could explore how well these positive emotion-focused coping strategies work in the context of extreme acute stress and chronic stress and in response to recalling traumatic memories.

Given that we tested our experiments in a laboratory or MRI setting, we were unable to examine how individuals use positive emotion-focused coping in everyday life. Additionally, we only chose to explore two different kinds of positive coping strategies: positive reminiscence and positive meaning finding. There are many other strategies that may be more/less effective for counteracting acute stress and negative recall. For instance, we can approach a situation with optimism or humor (Sharot, Riccardi, et al., 2007; Wu et al., 2013), use guided imagery (imagine a peaceful waterfall or quiet beach; e.g., Fredrickson, Mancuso, Branigan, & Tugade, 2000), be present-focused (practicing mindful awareness; e.g., Bishop et al., 2004), engage in mental time travel (e.g., daydreaming about the future), or celebrate and share positive experiences with other people (Lambert et al., 2012; Quoidbach et al., 2009)—all of which bolster positive emotions. It will be important for future research to use more naturalistic designs (e.g., experience sampling paradigms) to observe how different positive emotion-focused coping strategies naturally unfold over time to help us regulate negative affective states in our daily lives.

Another factor we did not thoroughly investigate was how the quality or context of memory might impact our findings. With regard to positive reminiscence as an emotion regulation strategy, there may be qualities of such memories that influence how beneficial they are in reducing stress, such as vividness and their social context (e.g., who was present in the memory with them). Although this was not the focus of the present dissertation, we explored this question in a separate report. A re-analysis of cortisol data from Experiment 2 showed that individuals who underwent stress but recalled positive memories that were rich in social context (with socially close others) had the greatest reduction in stress hormone levels, even when controlling for positivity (Speer & Delgado, *in revision*), suggesting that it may serve as social support under stress. With regard to updating negative memories with positive content, there may be initial aspects of a memory that make it more/less susceptible to modification. For instance, memories that are extremely negative, vivid and rich to begin with might be more difficult to change. There may also be aspects of a memory, beyond its emotion rating, that change after they are updated. Beyond observing increased positivity at future retrieval, positive meaning finding may also lead to reductions in the vividness and richness of a negative memory, or increases in its social context, by making you feel closer to the individuals who experienced the event with you.

This research also did not fully explore individual differences in the successful use of positive emotion-focused strategies. As described in the prior section, individuals with high resilience or who more frequently savor positive emotions in their daily lives might naturally be better at, find it easier to use, or may benefit more from positive emotion-focused coping. Individuals with anhedonia or depressive symptoms may fair the worst in using these strategies, given deficits in emotion regulation and difficulty recalling specific

positive autobiographical memories (Young et al., 2011). Our data supported both of those notions, but we were limited in fully testing this question given our small sample sizes of individuals who used positive meaning finding in each study, particularly in our fMRI experiments. Using a larger sample size, future research should explore age, gender, personality characteristics (high self-esteem), and clinical symptoms (resilience, depression) relating to the ease/difficulty in using positive emotion-focused strategies. Delineating the behavioral and neural deficits when positive emotion regulation fails could help inform clinical treatment.

Another potential limitation was that we used different neuroimaging analysis procedures across our two different fMRI experiments. Specifically, we analyzed brain data using BrainVoyager in Experiment 2 and then using SPM/FSL in Experiment 7. The reason for this change was primarily driven by greater knowledge of best practices in research and the goal of making our data shareable in the open science community, which could be accomplished with SPM/FSL but not BrainVoyager. Although this change might have made it more challenging to compare findings across fMRI experiments, this ended up not being the case, and this shift was an overall strength by making our data and analyses more accessible to other researchers.

5.4 Conclusions

This dissertation highlights the behavioral and neural components of savoring positive emotions for coping with negative affective states we experience in everyday life. We find converging evidence across behavioral, acute stress, neuroendocrine, and neuroimaging methods that reminiscing about the past and positive meaning finding can

help us deal with acute stress and negative affect elicited by our own negative autobiographical memories. Importantly, our findings support the notion that savoring positive emotions can help build psychological resources leading to enhanced coping and resilience to future adversity. We shed light on the relationship between neurobiological systems supporting autobiographical memory retrieval, positive emotion and its regulation of negative affect. This research may have clinical implications for individuals who are more susceptible to negative affective states (e.g., anxiety, mood or stress-related disorders) and who not only have difficulty regulating their emotions, but in using positive emotion-focused coping in particular.

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Table 2.1. Regions activated in a whole-brain parametric modulation of subjective feeling ratings during memory recollection for Stress-Positive individuals. $P < 0.01$, corrected.

			Talairach coordinates				
Region	BA	Laterality	x	y	z	Cluster Extent (mm^3)	t statistic
VLPFC	47	L	-31	13	-12	341	5.00
Middle Temporal Gyrus	21	L	-64	-17	-12	1997	6.55
Middle Temporal Gyrus	21	L	-52	-32	-6	1234	5.16
VLPFC	47	R	35	22	-3	757	6.00
NAcc/Caudate	48	R	14	19	-3	313	5.36
MPFC	9,10,125,32		-4	46	-3	8874	7.28
PCC	23		5	-53	15	460	5.59
Angular Gyrus	39	R	38	-68	33	347	5.30
Precuneus	7		-4	-62	39	357	4.71
Angular Gyrus	39	L	-43	-71	39	4476	7.73
DMPFC	8,9		-4	46	45	1389	6.03

BA = Brodmann Area; L = left side; R = right side

Table 2.2. Regions activated in a whole-brain parametric modulation of subjective feeling ratings during memory recollection for Stress-Positive > Stress-Neutral. P < 0.01, corrected.

Region	BA	Laterality	Talairach coordinates			Cluster Extent (mm^3)	t statistic
			x	y	z		
VLPFC	47	R	35	22	-3	251	5.38
Angular Gyrus	39	R	35	-71	33	274	5.20
DLPFC	8,9	L	-52	22	33	415	5.79
Angular Gyrus	39	L	-43	-71	39	2610	7.92

BA = Brodmann Area; L = left side; R = right side

Table 2.3. Regions showing positive psychophysiological interaction with right VLPFC as a function of increasing positive feeling ratings during memory recall for Stress-Positive individuals. $P < 0.01$, corrected.

			Talairach coordinates				
Region	BA	Laterality	x	y	z	Cluster Extent (mm^3)	t statistic
Seed: VLPFC	47	R	35	22	-3	757	
PPI Feeling							
DLPFC	9	L	-46	22	18	319	5.64

BA = Brodmann Area; L = left side; R = right side

Table 2.4. Regions activated in a whole-brain contrast of gain and loss trials in the monetary reward task. $P < 0.01$, corrected.

Region	BA	Laterality	Talairach coordinates x	y	z	Cluster Extent (mm^3)	t statistic
Gain > Loss							
NAcc/Ventral striatum		R	14	4	-6	965	6.34
NAcc/Ventral striatum		L	-10	4	-6	716	6.27

BA = Brodmann Area; L = left side; R = right side