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Encoding negative events under stress: High subjective arousal is related to accurate emotional memory despite misinformation exposure ☆

Siobhan M. Hoscheidt [a,b,*], Kevin S. LaBar [a,b], Lee Ryan [c], W. Jake Jacobs [c], Lynn Nadel [c]

[a] Center for Cognitive Neuroscience, Duke University, Durham, NC, USA
[b] Department of Psychology and Neuroscience, Duke University, Durham, NC, USA
[c] Department of Psychology, University of Arizona, Tucson, AZ, USA

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ABSTRACT

Stress at encoding affects memory processes, typically enhancing, or preserving, memory for emotional information. These effects have interesting implications for eyewitness accounts, which in real-world contexts typically involve encoding an aversive event under stressful conditions followed by potential exposure to misinformation. The present study investigated memory for a negative event encoded under stress and subsequent misinformation endorsement. Healthy young adults participated in a between-groups design with three experimental sessions conducted 48 h apart. Session one consisted of a psychosocial stress induction (or control task) followed by incidental encoding of a negative slideshow. During session two, participants were asked questions about the slideshow, during which a random subgroup was exposed to misinformation. Memory for the slideshow was tested during the third session. Assessment of memory accuracy across stress and no-stress groups revealed that stress induced just prior to encoding led to significantly better memory for the slideshow overall. The classic misinformation effect was also observed – participants exposed to misinformation were significantly more likely to endorse false information during memory testing. In the stress group, however, memory accuracy and misinformation effects were moderated by arousal experienced during encoding of the negative event. Misinformed-stress group participants who reported that the negative slideshow elicited high arousal during encoding were less likely to endorse misinformation for the most aversive phase of the story. Furthermore, these individuals showed better memory for components of the aversive slideshow phase that had been directly misinformed. Results from the current study provide evidence that stress and high subjective arousal elicited by a negative event act concomitantly during encoding to enhance emotional memory such that the most aversive aspects of the event are well remembered and subsequently more resistant to misinformation effects.

1. Introduction

Witnessing a disturbing event such as an act of violence is likely to elicit arousal and to be stressful. Research conducted in the area of emotion and memory has provided substantial evidence that stress influences long-term memory processes (see de Quervain, Aerni, Schelling, & Roozendaal, 2009 for review). These effects vary as a function of several modulatory factors, such as the stage of memory processes influenced by stress and the arousing nature of to-be-remembered materials (Buchanan & Lovallo, 2001; Cahill, Gorski, & Le, 2003; Jelicic, Geraerts, Merckelbach, & Guerrieri, 2004; Kuhlmann et al., 2005). Stress induced just prior to encoding has been shown to preserve or enhance memory for negative emotional, relative to neutral, information (Payne et al., 2006, 2007).

Enhanced emotional memory in this context may be attributed in part to the interaction of arousal-based modulation of perception and attention systems and the concomitant influence of stress hormones on brain regions involved in emotion and memory. Negatively arousing materials and events influence perceptual and attentional resources, implicitly biasing perception and attention towards aversive information (Alpers, 2008; Bradley, Hamby, Low, & Lang, 2007; Calvo & Lang, 2005; Nobata, Hakoda, & Ninose, 2010; Nummenmaa, Hyönä, & Calvo, 2006). Spontaneous preferential allocation of attention and perception towards aversive information creates circumstances under which this information has privileged access to further processing in long-term memory systems (see Compton, 2003 for review). Stress-based activation of

* Corresponding author. Address: C03J Levine Science Research Center, Duke University, Box 90999, Durham, NC 27708, USA.
E-mail address: siobhan.hoscheidt@duke.edu (S.M. Hoscheidt).

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the hypothalamic–pituitary–adrenal (HPA) and sympathetic adrenomedullary (SAM) axes further facilitates processing of emotional information in memory systems, triggering the release of stress hormones (i.e. cortisol and adrenaline/noradrenaline) that enhance neural plasticity (Duvarci & Paré, 2007) and increase functional activation in the amygdala (van Stegeren et al., 2005, 2007), a brain region critical for emotional learning (Buchanan & Adolphs, 2002; Canli, Zhao, Brewer, Gabrieli, & Cahill, 2000). Stress hormones also affect learning in the hippocampus, a region of the brain that plays an integral role in episodic memory. Although stress hormones, such as cortisol, can have impairing effects on hippocampal function overall (Dedovic et al., 2009; Henckens, Hermans, Pu, Joëls, & Fernández, 2009; Pruessner et al., 2008), stress hormone-driven facilitation of neural plasticity within the amygdala influences the hippocampus (Strange & Dolan, 2004) by potentiating learning in this region (Kukolja, Klingmuller, Maier, Fink, & Hurlemann, 2011). In this way, stress and arousal likely interact to create ideal behavioral and neurophysiological conditions for optimal encoding of negative emotional information.

A study conducted by Payne et al. (2007) illustrates that emotional memory enhancement effects depend, at least in part, on the interaction of stress and arousal during encoding. In this study participants underwent a psychosocial stress induction, or control task, after which they viewed identical slideshows (Cahill, Prins, Weber, & McGaugh, 1994) with differing narrations. One group heard a negatively arousing story about a violent car crash and surgical procedures performed on victims of the car wreck. By contrast, the other group was told a story about procedures involved in a standard hospital drill. One week later, participants in the stress/negatively-arousing narration group showed significantly better memory for the slideshow compared to the no stress group. By contrast, memory performance in the stressed/non-arousing slideshow condition was impaired (see also Payne et al., 2006). These results provide evidence that concomitant activation of stress and arousal during encoding create ideal cognitive-neurobiological conditions for negative emotional information to be strengthened in memory.

Somewhat independently, research investigating the fidelity of eyewitness memory has provided ample evidence that people exposed to misleading information often remember false details as veridical components of an experienced event (for a recent review see Loftus, 2005). This phenomenon, known as the misinformation effect (Loftus, 1975; Loftus & Hoffman, 1989; Loftus & Palmer, 1974), has been reported in a multitude of studies and has, over the years, become a classic demonstration of the susceptibility of episodic memory to distortion. From the time of its discovery in the late 1970s, the misinformation effect has had clear implications in the legal domain, providing empirical evidence that in the face of misleading information eyewitness memory is prone to fallibility. Traditionally, studies of misinformation have involved post-event exposure to a single critical piece of misinformation after which subsequent endorsement of the misleading detail is typically observed (Loftus, 1975; Loftus & Palmer, 1974). For example, in the original studies of the misinformation effect (e.g. Loftus, Miller, & Burns, 1978) participants viewed a series of slides that depicted a car running through a stop sign and striking a pedestrian. Later, a subgroup of participants was exposed to a misleading detail when asked, "how fast was the car going when it ran through the yield sign?" The misinformed subgroup was subsequently more likely to erroneously report that the car had run through a yield sign, compared to their non-misinformed counterpart. Misinformation effects also occur when multiple items are misinformed (Cann & Katz, 2005; English & Nielson, 2010; Tomes & Katz, 1997, 2000; Zhu et al., 2012). In such cases memory for an event may become highly distorted after exposure to a number of misleading details (Luna & Migueles, 2009; Okado & Stark, 2005).

Emotional memory enhancement effects, presumably driven by the interaction of stress and arousal during encoding, have interesting implications for eyewitness accounts, which in real-world contexts frequently involve negatively arousing events that likely elicit activation of the physiological stress response and ensuing release of stress hormones. Although negatively arousing events may be subsequently well remembered, this may or may not preclude these memories from susceptibility to misinformation endorsement. Indeed, in some cases memory for negative materials and events has been shown to be more susceptible to incorporation of false information compared to memories for positive or neutral materials (Nourkova, Bernstein, & Loftus, 2004; Porter, Bellhouse, McDougall, ten Brinke, & Wilson, 2010; Porter, Spencer, & Birt, 2003; Porter, Taylor, & ten Brinke, 2008). For example, despite the fact that publicized negative events are typically well remembered, memory for these events is nonetheless susceptible to incorporation of false details (Granhag & Strömwell, 2002; Nourkova et al., 2004; Ost, Vrij, Costall, & Bull, 2002; Porter et al., 2008). From this contradiction arose the notion that although negative emotion generally facilitates memory it may also increase susceptibility to misinformation (Paradoxical Negative Emotion hypothesis; Porter et al., 2008). Some evidence, however, argues against this notion. For example, higher levels of self-reported emotional impact of an eyewitness event have been associated with greater memory accuracy. Furthermore, in such cases subsequent memory reports remain highly accurate despite exposure to false post-event information (Odinot, Wolters, & van Koppen, 2009).

Some studies have demonstrated that stress has overall deleterious effects on eyewitness memory (for review see Deffenbacher, Bornstein, Penrod, & McGorty, 2004; Valentine & Mesout, 2009) whereas others have shown that memory is preserved. For example, Morgan et al. (2004) investigated memory accuracy for an abusive interrogator in individuals undergoing military training. Participants were randomly assigned to high- and low-stress interrogation contexts after which recognition memory for the interrogator was assessed using live line-up and photo-spread methods. Results revealed that more participants in the low-compared to high-stress group had better eyewitness memory, specifically memory for features of the individual who interrogated them. On the contrary, other studies have shown that high subjective stress during encoding predicts highly accurate subsequent memory for an aversive witnessed event (for review see Christianson, 1992). This finding has been reported in cases of eyewitness memory for crimes such as robbery, physical assault and murder where high subjective ratings of stress and arousal experienced during the witnessed event related to highly accurate memory for the event (e.g. 96% accuracy) directly, and for a number of months, following the event (Odinot et al., 2009; Woolnough & MacLeod, 2001; Yuille & Cutshall, 1986).

While investigations of the fidelity of eyewitness memory have been informative in their own right, interpretations of results in light of the effects of stress and/or arousal on memory and subsequent misinformation effects remains unclear. As results are mixed, it is important to investigate factors known to influence memory processes in a manner that could moderate misinformation effects. Critical factors in this regard include the role of stress and emotional arousal, both likely activated during encoding of an eyewitness event and, as previously discussed, are known to influence multiple memory processes (Buchanan & Lovallo, 2001; Cahill & Alkire, 2003; Chamberlain, Müller, Blackwell, Robbins, & Sahakian, 2006; Harris & Pashler, 2005; Kuhlmann and Wolf, 2006; Laney, Campbell, Heuer, & Reisberg, 2004). Regarding laboratory studies of misinformation effects interactions of stress and arousal, particularly arousal evoked by a to-be-remembered event, have typically not been examined. Furthermore, to our knowledge, a systematic examination of these factors on memory and misinformation effects has yet to be reported. Understanding how stress and arousal interact to influence memory for a negative event, and potentially act concomitantly to moderate misinformation effects, is relevant to better understanding emotional memory and the veracity of eyewitness testimony.

Therefore, the goal of the present study was to examine subsequent effects of misinformation exposure on memory for a negative arousing to-be-remembered event encoded under stress. We adapted slideshow materials from Payne et al. (2006) and added a misinformation manipulation 48 h after encoding and 48 h prior to memory testing. To assess misinformation effects for aversive and non-aversive phases of the slideshow misinformation was presented in a multi-trial design (e.g. Cann & Katz, 2005; Tomes & Katz, 1997, 2000). Each slide of the slideshow was associated with five misinformed details during the misinformation manipulation, and subsequent endorsement of these details was assessed during memory testing. Subjective arousal was assessed using the state component of the State-Trait Anxiety Inventory (STAI-state) and salivary cortisol was collected as an objective biomarker of stress reactivity. Here we ask whether stress at encoding could preserve or enhance memory for aversive aspects of an eyewitness event, or for the arousing event overall, such that it is subsequently less vulnerable to misinformation effects.

Our predictions were as follows: (1) as reported in our previous work (Payne et al., 2007), memory for the slideshow would be enhanced in the stress, compared to the no-stress, group; (2) misinformed participants would show the classic misinformation effect overall, (3) stress-driven emotional memory enhancement may result in misinformed-stress participants being less likely to incorporate false information into the most aversive phase of the slideshow, and (4) stress and arousal would interact such that individuals in the stress group who reported being highly aroused by the negative slideshow during encoding would have relatively accurate memory for items that were directly misinformed, and endorse fewer misinformed details, specifically for the most aversive slideshow phase.

2. Methods and materials

2.1. Participants

Sixty-eight undergraduate students (mean age 19 years; range 18–21 years; 30 females) recruited through the University of Arizona subject pool participated in and completed the study. Prescreening excluded individuals with a history of diagnosed psychopathology, learning disabilities, regular use of medications containing corticosteroids, or endocrine disorders. Participants were instructed to abstain from alcohol, caffeine, and exercise on days of experimental sessions. All participants provided written informed consent under a protocol approved by the University of Arizona Institutional Review Board and were given course credit in exchange for participation.

2.2. Design and procedure

Prior to the initial visit, participants were randomly assigned to a 2 (stress vs. control) $\times$ 2 (misinformation vs. no misinformation) between-subjects factorial design that yielded four experimental groups. The number of participants within each experimental group was as follows: no stress and no misinformation ($N = 21$); no stress and misinformation ($N = 20$); stress and no misinformation ($N = 12$) and stress and misinformation ($N = 15$). Lower numbers in the stress conditions resulted as a function of participants randomly assigned to the stress group being more likely to request to discontinue the experiment after being instructed that they were to give an impromptu speech in front of judges. Furthermore, some individuals who underwent the TSST procedure did not return for a subsequent visit. Age, level of education and distribution of gender did not significantly differ across the four groups. Three experimental sessions were held 48 h apart (see Fig. 1(A and B)). Experimental sessions were conducted between the hours of 1 pm and 5 pm to control for diurnal shifts in basal cortisol levels known to affect memory function (de Kloet, Oitzl, & Joëls, 1999; Lupien et al., 2002; Maheu, Collicutt, Komik, Moszkowski, & Lupien, 2005). Each of the three test sessions was held in a different room and was conducted by a different experimenter. This procedure was used to avoid inadvertently reactivating stress-induced states in stress-group participants and to increase ecological validity within the misinformation group, as witnesses are rarely exposed to misleading information in the same location as the original event.

On Visit One, participants engaged in a psychosocial stress induction (i.e. Trier Social Stress Test), or control task, after which they were escorted to an adjacent room to view a negatively arousing slideshow. To reduce suspicion that memory for the slideshow would later be tested, participants were led to believe that the purpose of the encoding task was to measure pupillary reflexes to various types of stimuli using infrared eye tracking. Before the beginning of the encoding task, participants were instructed to pay attention to each slide for the duration of its presentation. Forty-eight hours later participants returned to the lab to complete the second experimental visit.

Upon arrival participants were informed that they would be asked a series of questions about the slideshow they viewed two days prior. A total of 60 questions (5 questions pertaining to each of the 12 slides) were read to the participant by the experimenter. In the misinformation condition false information was embedded in each of the 60 questions as factual elements of the slideshow (e.g. "What did the boy have in his hands?" versus "What did the boy have in his hands *besides his lunch*?"). To avoid inadvertently cuing one group with information that could potentially benefit memory performance on Visit Three, questions were identical across non-misinformed and misinformed groups, with the exception of false details provided in the misinformation condition. Questions asked during this session were designed solely as a method of exposing participants in the misinformation group to false information. Experimenters took note of any comments made by the participant that indicated that s/he suspected they were being presented with false information. Responses were not considered a dependent measure of memory testing and were not analyzed. Subsequent review of participant responses revealed that none of the misinformed participants detected, or at least openly acknowledged, the presence of false information for any of the 60 questions.

Participants returned to the lab 48 h after questioning to complete the third and final experimental session. Upon arriving participants were told that their memory of the slideshow would be tested. Memory was assessed using a four-alternative force choice recognition test that consisted of 136 questions in total (approximately 11 questions per slide) and was administered over a computer using the stimulus presentation program DMDX (Version 3.1.4.1, (Forster & Forster, 2003)). Questions used in the recognition task were taken directly from Payne et al. (2006). An example of a question asked during the recognition task is the following: "What was the color of the mother's sweater?" Four options were presented under the question from which the participant was instructed to choose only one. Examples of response options are the following: (1) blue, (2) white, (3) green, or (4) red. Recognition task questions were modified from the original Payne et al. (2006) study to include multiple-choice answers for misinformed items. Out of

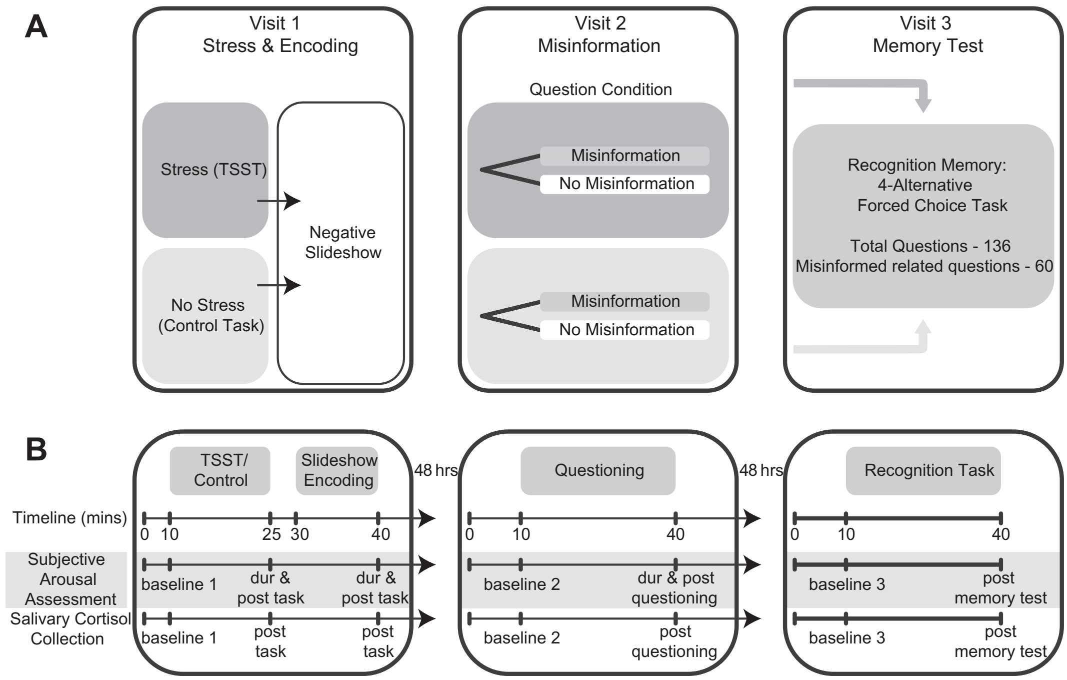

Fig. 1. Behavioral tasks performed (A) and assessment timeline for subjective arousal (i.e. STAI-state) and salivary cortisol (B) across the three experimental visits.

the 136 questions, 60 questions (5 questions for each of the 12 slides) provided an opportunity for choosing misinformation. For example, a question that was related to misinformation asked, "What was the boy carrying when they left the house?" Forty-eight hours prior to memory testing misinformed participants were led to believe that the boy was carrying his lunch. Answers that participants could choose from included the misinformed option "his lunch", two incorrect responses "a teddy bear" or "a backpack" and the correct answer "a soccer ball". The probability of choosing a correct response was 25% for all questions. For questions unrelated to misinformation, participants had a 75% chance of choosing an incorrect response. By contrast, questions associated with misinformation presented participants with a 25% probability of choosing a misinformed response and a 50% chance of choosing an incorrect response. Participants made responses using numbers on a keyboard. Since the time it took to complete the recognition task did not significantly differ across misinformation conditions in pilot work, we used a self-paced procedure for testing recognition.

2.3. Slideshow materials

A modified version of materials developed by Heuer and Reisberg (1990) and methods used by Cahill and McGaugh (1995), taken from Payne et al. (2007), were used to compare memory for the slideshow across stress and no stress groups. The slideshow is composed of 12 slides that can be divided into three separate phases based on the visual content of each slide. Phases are defined by temporal placement relative to an aversive phase that makes up the middle portion of the slideshow. The first four slides define the initial neutral (pre-aversive) phase that depicts a woman and child leaving a house, walking through a neighborhood and crossing a street. The next three slides define the aversive phase, composed of gruesome images that include a car wreck, a surgical team operating on an open body cavity, and a pair of legs that are bruised and sutured. The remaining five slides compose the final neutral (post-aversive) phase. This phase depicts the woman exiting a hospital, placing a phone call in a telephone booth, and hailing a cab. In the pre-aversive phase participants were told about a mother and son leaving their house in the morning to visit the father at work, a surgeon at a nearby hospital. During the aversive and post-aversive phases participants were told that upon arriving at the hospital the mother and son witnessed a surgical team (the father included) struggle to save victims that had been critically injured in a horrible car wreck earlier that day. The mother left the hospital distraught and called her boss to request the day off. The slideshow narration was presented to participants over headphones and consisted of a single sentence that described the slide. Each slide was presented for a total of 9 s to allow participants enough time for visual exploration after hearing the narration.

2.4. Misinformation materials

Misleading questions were created and piloted to ensure that false information would elicit an overall misinformation effect. Each question consisted of one major piece of false information that was presented as a factual element of the story. For example, the question "What else was the boy carrying besides his lunch?" was designed to lead participants to believe that the boy was carrying his lunch when he left the house. False details were created primarily from visual information that could be altered without changing the major thematic or emotional content of the storyline (i.e. focused on peripheral information; see Heuer & Reisberg, 1990; Talarico, Berntsen, & Rubin, 2009). Participants received a total of 60 misleading questions, 5 pertaining to each slide in the story (a total of 12 slides). The number of slides per slideshow phase differed (neutral – 4 slides; emotional – 3 slides; post-emotional – 5 slides), as did the number of misinformed questions asked pertaining to each of these phases (neutral – 20 questions; emotional – 15 questions; post-emotional – 25 questions). For this reason, mean percent of misinformation endorsed was calculated and analyzed across slideshow phases as well as across the entire slideshow.

2.5. Stress and control tasks

2.5.1. Trier social stress test

The Trier Social Stress Test (i.e. TSST) is a psychosocial stress induction task that exposes individuals to social evaluation threat and stressor uncontrollability during performance of a speech and a complicated math task (Kirschbaum, Pirke, & Hellhammer, 1993). The TSST is a well-established stress induction method used in laboratory settings to activate the HPA axis, which leads to the release of stress hormones (Maheu et al., 2005; Payne et al., 2006, 2007; Smeets et al., 2009; Wand et al., 2007; Zorawski, Blanding, Kuhn, & LaBar, 2006). The TSST was selected as a stress induction method for the current study over other methods (e.g. cold pressor task; Schwabe, Haddad, & Schachinger, 2008) because we aimed to replicate and extend the stress and memory effects reported by Payne et al. (2007).

Upon arriving at the lab, participants randomly assigned to the stress group were met by an experimenter wearing a white lab coat and were told that they would be given five minutes to prepare a speech meant to convince a panel of judges that s/he is the best candidate for a job position of the participant's choosing. To boost anticipatory anxiety related to task performance, participants were instructed to use only truthful personal information in their speech and were led to believe that a panel of a total of five judges trained in verbal and non-verbal behavior would evaluate their performance. Participants were told that three judges would remain behind a one-way mirror while two judges would sit in front of them. In addition, participants were led to believe that it was critical to the outcome of the experiment that they perform well on the task and that video cameras and a microphone would record their verbal and non-verbal behavior for subsequent computer analysis.

Participants had five minutes to prepare notes for the speech. After five minutes passed, two judges wearing white lab coats (one male and one female) entered the room and sat directly in front of the one-way mirror and microphone where the participant would deliver the speech. The experimenter unexpectedly took the prepared notes away from the participant and informed them that they would give their speech extemporaneously while the judges reviewed their notes. The experimenter escorted the participant to the microphone and handed the notes to the judges. To increase believability that judges were present behind the one-way mirror the experimenter engaged in a scripted dialog, with a recorded male voice, during a staged technical test of the microphone and video cameras. After the staged technical test the experimenter cued the participant to begin the speech and, in the event that the participant fell silent for more than 30 s during the task, prompted them to continue until the five minutes had ended. To enhance stress evoked by social evaluative threat during the speech, judges conveyed indifference towards the participant at all times. Judges did not talk to participants, did not provide non-verbal signals of approval or disapproval (e.g. head nodding or shaking), maintained neutral facial expressions, took notes on a clipboard, and reviewed notes the participant had prepared for the speech. If at any time the participant asked for clarification about any part of the task, the experimenter provided further information. After five minutes of the public speaking task, the pre-recorded male voice cued the participant to end their speech, informed them of a surprise math task and provided task instructions. Participants were asked to subtract by 17, beginning with the number 1873, as quickly and as accurately as they could until told to stop. Participants were required to verbalize their answers into the microphone, were asked to subtract faster as the task progressed, and were told to begin over again (i.e. at 1873) if they answered incorrectly. After five minutes, the recorded male voice informed participants to stop the subtraction task, which marked the end of stress induction period.

2.5.2. Control task

Participants randomly assigned to the no-stress group performed a similar set of cognitive tasks but without a social evaluative threat component. Upon arriving at the lab, participants were met by the experimenter and told that they would perform a series of written tasks. To parallel the speech preparation and presentation, participants performed a pencil-and-paper sentence-completion task for five minutes. After the allotted time elapsed, participants were instructed to read the completed sentences aloud but quietly to themselves and were timed for an additional five minutes. Finally, participants were asked to complete a simple paper and pencil math task consisting of elementary subtraction problems. They were given five minutes to complete as many as they could.

2.6. Stress and subjective arousal measures

2.6.1. Subjective arousal ratings

The state component of the State-Trait Anxiety Inventory (STAI-state) is widely used to measure transient feelings of apprehension and uneasiness (Spielberger, Reheiser, Hilsenroth, & Segal, 2004). While the STAI has traditionally been used to assess subjective reports of state anxiety, there have been growing concerns in the field that this measure is more representative of subjective negative affective state (Bados, Gómez-Benito, & Balaguer, 2010) and has shown to correlate with measures of physiological arousal (Grös, Antony, Simms, & McCabe, 2007; Kantor, Endler, Heslegrave, & Kocovski, 2001; Noto, Sato, Kudo, Kurata, & Hirota, 2005). In the current experiment, the STAI-state was collected as an assessment of subjective arousal at ten time points throughout the experiment: (1) upon arrival visit one, (2) and (3) during and immediately after the stress or control task, (4) and (5) during and after slideshow encoding, (6) upon arrival visit two, (7) and (8) during and after questioning, (9) upon arrival visit three, and (10) at memory testing (see Fig. 1). STAI-state measures that assessed subjective arousal during task performance are retrospective reports of how participants felt while engaged in a particular task. STAI-state measures reported during and after the TSST served as a manipulation check for the psychosocial stress induction. Ratings collected during slideshow encoding served as an assessment of transient negative affect experienced in response to exposure to the negatively arousing story.

2.6.2. Saliva sampling methods

Salivary cortisol, a reliable index of bioavailable free cortisol (Hellhammer, Wust, & Kudielka, 2009), was collected to assess one component of the physiological stress response with respect to our stress manipulation. Saliva samples were collected at the beginning of each of the three visits as a measure of baseline cortisol. To assess task-related changes in cortisol levels relative to baseline measures, additional samples were collected at the following times: (1) immediately after the speech or control task, (2) after slideshow encoding (~20 min post stress induction), (3) after the misinformation session, and (4) during memory testing (see Fig. 1). Before the first visit, participants were instructed to not apply Chap Stick, lip-gloss or lipstick, to abstain from drinking caffeine, and to not exercise on the day of each experimental visit. At the beginning of each session, ten minutes before saliva collection, each participant was required to rinse his or her mouth with water for one minute to remove oral contaminants (e.g. food ruminants) from the mouth before sampling. After rinsing, participants were told that they could not eat or drink for the duration of the experimental session. At the time of sampling, the participant tipped a conical centrifuge tube up to his/her mouth and, without touching it to the lips, let the swab fall into their mouth. The participant then lightly chewed the swab for one minute, saturating it with as much saliva as possible. After one minute, the experimenter instructed the participant to spit the swab back into the tube, without touching the tube to their mouth. Saliva samples were placed in a freezer for storage within ten minutes of collection to prevent bacterial growth, which can compromise assay validity (Whembolua, Granger, Singer, Kivlighan, & Marguin, 2006). Samples remained frozen at −20 °C until analyzed. Salivary cortisol samples collected as a biomarker of physiological stress were analyzed for 66 (no-stress group; $N = 39$; stress group; $N = 27$) of the 68 participants due to insufficient sampling for two individuals.

2.6.3. Saliva sampling device and analysis

Saliva samples were collected using Salimetrics Oral Swabs (SOS) manufactured by Salimetrics Inc (State College, P.A.). SOSs are made from inert polymer, shaped into 30 × 10 mm cylinders, stored in a capped, conical centrifuge tube with a separate tube insert that has a hole in its bottom to allow passage of saliva sample into the conical centrifuge tube during centrifuging. Polymer is preferable over cotton swabs, traditionally used for saliva collection, because it is highly absorbent but allows for maximal amount of sample to be extracted and yields greater cortisol recoveries. Additionally, polymer has been reliably shown to not interfere with salivary immunoassay results, a problem that has been demonstrated with the use of cotton-based sample collection methods (Granger et al., 2007; Groschl & Rauh, 2006; Shirtcliff, Granger, Schwartz, & Curran, 2001). Free cortisol was analyzed using solid phase enzyme-linked immunosorbent assay (ELISA) kits manufactured by IBL International (Hamburg, Germany).

2.7. Statistical analyses

All analyses were conducted using the data analysis program IBM SPSS Statistics (Version 19.0. Armonk, NY: IBM Corp). Main effects and interactions were tested using mixed-model ANOVAs. Correlational analyses were also conducted to examine relationships between independent and dependent variables.

2.7.1. Salivary cortisol and subjective arousal

To confirm that the TSST was an effective method of stress induction in the current experiment, STAI-state ratings (i.e. subjective arousal) and salivary cortisol measures were submitted as within-subject factors into separate mixed-model ANOVAs with stress group as a between-subject factor.

2.7.2. Recognition memory for veridical information

Recognition memory scores were analyzed to test the prediction that memory for a negatively arousing story would be better in the stress group, compared to the no-stress group, as reported by Payne et al. (2007). Slideshow phase was included in the analysis to examine whether the aversive phase of the slideshow was better remembered than the neutral pre- or post-phases (see Payne et al., 2006). Memory accuracy for each slideshow phase was calculated using questions on the recognition task that did not involve misinformation. This procedure was done to examine memory accuracy in all participants, including those that were misinformed, while excluding misinformation effects (e.g. Tomes & Katz, 1997).

2.7.3. Recognition memory for misinformation

To test our prediction that misinformed individuals would be more likely to endorse misinformation overall, the misinformation effect was assessed by examining whether misinformed, compared to non-misinformed, participants were significantly more likely to endorse misinformed items on the recognition task. Furthermore, we speculated that stress-misinformed participants might endorse fewer misinformed details, compared to the no stress-misinformed group, for the most aversive phase of the slideshow. The mean percent of misinformation endorsed across the 60 recognition items that corresponded to false details provided during the questioning session was calculated across slideshow phases and submitted to a mixed-model ANOVA. Slideshow phase and stress group was included in the analysis to examine whether these factors interacted with misinformation effects.

2.7.4. Correlations between stress, arousal and misinformation

Correlational analyses were used to test our hypothesis that stress and arousal would uniquely interact to moderate misinformation effects in individuals who were misinformed. We predicted that individuals in the misinformed stress group who reported being highly aroused by the negative slideshow would have relatively accurate memory for items directly misinformed, and endorse fewer misinformed details, specifically for the most aversive slideshow phase.

3. Results

3.1. Stress and subjective arousal

As expected, exposure to the TSST significantly elevated both physiological stress and subjective arousal. ANOVA results for salivary cortisol data revealed a significant group × cortisol interaction ($F_{[2,124]} = 9.45$, $P < 0.0001$, $\eta_p^2 = .13$) (Fig. 2A). As predicted, follow up t-tests indicated that cortisol levels were significantly greater in the stress group (compared to the no-stress group) directly after the experimental manipulation (i.e. TSST or control task) ($t(64) = 3.45$, $p = 0.001$) and during slideshow encoding ($t(64) = 3.95$, $p = 0.0001$). Furthermore, within the stress group cortisol levels were significantly elevated (relative to baseline) immediately after stress induction ($t(26) = 4.76$, $p = 0.0001$) and remained significantly elevated during slideshow encoding ($t(26) = 4.09$, $p = 0.0001$). No other comparisons between groups were significant.

Consistent with cortisol findings, ANOVA results for subjective arousal yielded a significant group × subjective arousal interaction ($F_{[4,248]} = 2.89$, $P < 0.023$, $\eta_p^2 = .05$) (Fig. 2B). As predicted, follow up *t*-tests indicated that subjective arousal response was significantly greater in the stress, compared to the no-stress, group during ($t(64) = 2.83$, $p = 0.006$) and immediately after ($t(64) = 2.25$, $p = 0.028$) the experimental manipulation. Furthermore, within the stress group exposure to the stress task significantly increased subjective arousal both during ($t(26) = 5.69$, $p = 0.0001$) and directly after stress induction ($t(26) = 3.31$, $p = 0.003$) compared to baseline. No other comparisons between groups were significant.

3.2. Recognition memory

3.2.1. Memory accuracy

Results yielded a significant main effect of stress group ($F_{[1,64]} = 4.95$, $P < 0.030$, $\eta_p^2 = .07$). As predicted, stress at encoding significantly enhanced memory for the negatively arousing story overall (Fig. 3). Memory accuracy did not significantly differ across slideshow phase as a function of stress group ($F_{[2,128]} = 2.03$, $P = .136$, $\eta_p^2 = .03$).

3.2.2. Misinformation effect

Results yielded a significant main effect of misinformation condition ($F_{[1,63]} = 51.64$, $P < 0.0001$, $\eta_p^2 = .442$), showing that misinformed participants were significantly more likely than their non-misinformed counterpart to endorse misinformation at memory testing (Fig. 4). Contrary to our hypothesis a significant three-way interaction between stress group, misinformation condition and story phase was not found ($F_{[2,128]} = 0.53$, $P = 0.59$, $\eta_p^2 = .02$). Failure to observe the predicted interaction, however, is likely

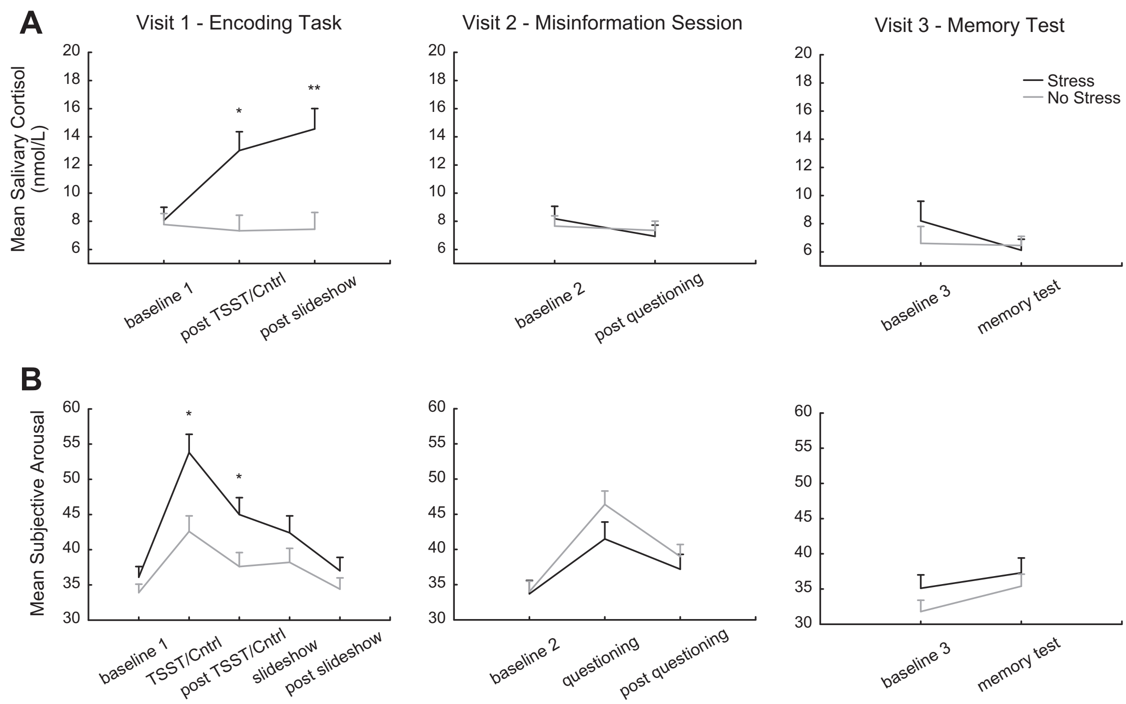

Fig. 2. Mean salivary cortisol (A) and subjective arousal ratings (B) for stress and no stress groups across all time points for the three experimental visits. The stress group showed significantly increased salivary cortisol directly after the stress manipulation and during slideshow acquisition compared to the no stress group. The stress group also showed significantly elevated subjective arousal ratings, relative to the no stress group, during and after the stress manipulation. Error bars represent the standard error of the mean.

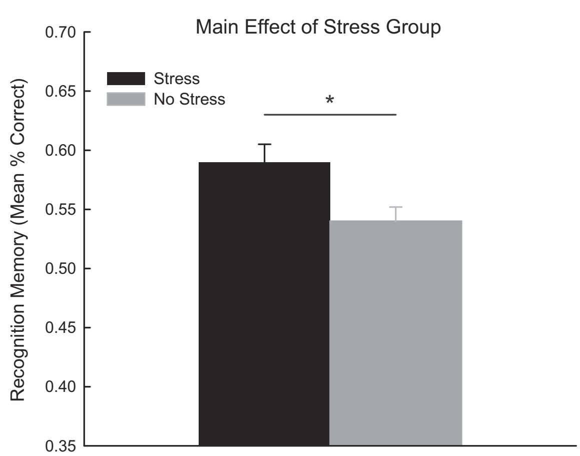

Fig. 3. Main effect of stress at encoding. The stress group showed significantly better memory for the slideshow overall, compared to the no stress group. Error bars represent the standard error of the mean.

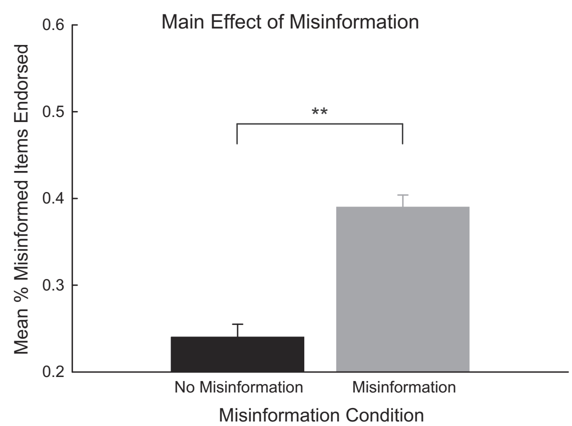

Fig. 4. Main effect of misinformation exposure. Participants exposed to misinformation were significantly more likely to endorse false information at memory testing, compared to non-misinformed participants. Error bars represent the standard error of the mean.

the result of smaller sample sizes within the stress group. This limitation is reviewed in the discussion section.

3.2.3. Stress, arousal and misinformation endorsement

As predicted, in the misinformed stress group only high subjective arousal ratings during slideshow encoding related to increased resistance to misinformation endorsement, specifically for the aversive slideshow phase ($r(15) = .598$, $p = 0.019$); misinformed no-stress group ($r(20) = .049$, $p = .839$ (NS); correlation difference between groups: $Z = -1.76$, $p = .039$ (one-tailed)) (Fig. 5(A and B)). Furthermore, in the misinformed stress group high subjective arousal during encoding related to more accurate memory for aversive phase items that had been directly misinformed ($r(15) = .807$, $p = 0.0001$; misinformed no-stress group ($r(20) = .334$, $p = .150$ (NS); correlation difference between groups: $Z = 2.12$, $p = .017$ (one-tailed)) (Fig. 5(C and D)). Correlational analyses for the other slideshow phases were not significant.

Cortisol was also analyzed to determine if an objective measure of stress during encoding correlated with memory performance, as subjective arousal ratings did. This measure, however, did not yield significant results in the correlational analyses, despite showing clear effects in response to the stress manipulation itself (Fig. 2A). Potential explanations for this are reviewed in the discussion section.

4. Discussion

Understanding how stress and arousal interact to influence memory for a witnessed event and subsequently moderate

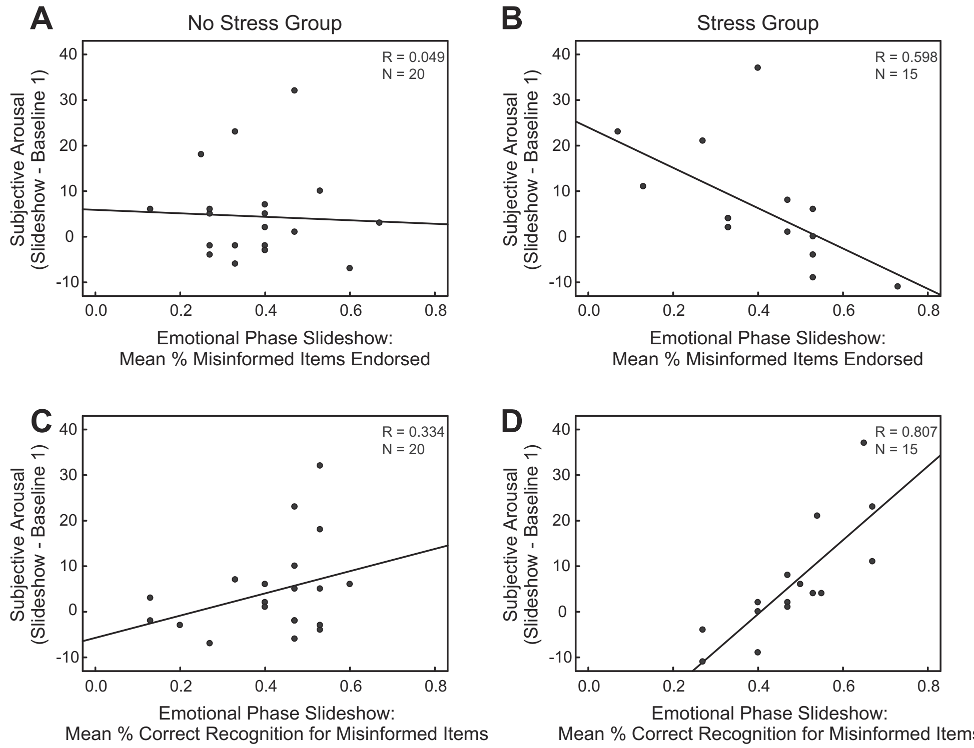

Fig. 5. Correlations between subjective arousal during slideshow encoding (i.e. arousal slideshow – arousal baseline visit one), percent of misinformed items endorsed and percent correct responses for misinformed items across stress and no-stress groups, for the aversive slideshow phase. Stress-misinformed participants that experienced higher, relative to lower, subjective arousal during encoding were less likely to endorse misinformation for the aversive slideshow phase (B) and showed better memory for components of the aversive story phase that had been directly misinformed (D). Correlations were N.S. in the no-stress group (A and C).

misinformation effects is relevant to understanding behavioral mechanisms that contribute to eyewitness testimony. Witnessing a disturbing event, such as an act of violence, is likely to be stressful and exposure to such a negative event likely induces high states of arousal. To date, a systematic examination of the influence of these factors on memory accuracy and misinformation effects has yet to be reported. The primary purpose of the present study was to examine subsequent effects of misinformation exposure on memory for a negatively arousing to-be-remembered event encoded under stress. Our previous work has shown that stress at encoding enhances memory for a negatively arousing story (Payne et al., 2007). In the current study we aimed to replicate this finding, and we predicted that stress- and arousal- mediated enhancement of emotional memory representations might lead to better retention of the most negatively-arousing portion of the slideshow and increase resistance to subsequent misinformation endorsement.

Consistent with our previous findings (Payne et al., 2007), results showed that stress prior to encoding affects memory for a negative event by enhancing subsequent memory. This finding provides further support for the notion that stress influences encoding of aversive events, likely by the biasing of attentional processes towards emotionally salient stimuli during encoding (Brosch, Pourtois, & Sander, 2010; Huang & Luo, 2006; Nummenmaa et al., 2006; Ohman, 2005; Talmi, Anderson, Riggs, Moscovitch, & Caplan, 2008) and the preferential strengthening of emotional memory representations by stress hormones during encoding and consolidation (Buchanan & Lovallo, 2001; Cahill et al., 2003; de Quervain et al., 2009, review; Nielson & Powless, 2007). Although stress enhanced memory for the aversive story overall, stress alone did not moderate misinformation endorsement. It is important to note, however, that small sample sizes in the current study likely limited our ability to observe significant interactions between variables of interest. Further investigation will be needed to examine whether stress alone moderates misinformation effects. Critically our investigation of effects of exogenously-induced stress and arousal associated with encoding an aversive event revealed that this high stress-arousal combination increased resistance to misinformation endorsement, possibly as a result of better retention for emotional items. Participants that were stressed prior to encoding, and reported that they were highly aroused by the thematically negative event, were subsequently less likely to endorse misinformation for the most negatively-arousing portion of the slideshow. Furthermore these participants had more accurate memory for items that had been directly misinformed within this slideshow phase. These results provide further support that stress enhances memory for negative arousing events and extends this finding into the domain of misinformation, demonstrating that stress- and arousal-mediated emotional memory enhancement effects reduce vulnerability of emotional information to misinformation. With respect to eyewitness memory, the current results suggest that arousal induced by a witnessed event, in combination with activation of a stress state, results in enhanced emotional memory that is subsequently less vulnerable to the incorporation of false details despite direct exposure to misleading information.

In discussing our results as they relate to eyewitness memory in the real world, one must consider limitations of laboratory designs. First, it is important to consider differences in memory performance for emotional events as defined in the laboratory compared to those encountered in the real world. For example, in the case of a real life assault, it is probable that attention will be diverted to components of the situation that are most relevant to survival. By contrast, emotional events in the laboratory likely do not activate survival mechanisms but do elicit an arousal response that biases attention and encoding processes towards emotionally salient information. A study conducted by Ihlebaek, Løve, Eilertsen, and Magnussen (2003) provided evidence that when memory for an eyewitness event is compared across laboratory (i.e. video) and live conditions, individuals who viewed the event via video had better memory for the event than those who were physically present. Passive viewing of a negatively arousing event in a laboratory setting likely allows a broader allocation of attention that is not disrupted by dramatic shifts in attention driven by survival mechanisms. Though in the current experimental design we show that the interaction of stress and arousal evoked by a negative to-be-remembered event leads to better memory performance, and fewer misinformed items endorsed for emotional information, in a real-world eyewitness situation this may be true only for those aversive aspects of the event most pertinent to survival. We also must consider that the primary measure of arousal in the current study is subjective report without accompanying objective (e.g. galvanic skin response, heart rate variability), measures. While subjective arousal ratings is a reliable correlate of physiological arousal (Kantor et al., 2001), the use of this single dependent variable limits us from a broader discussion of physiological mechanisms of arousal that may interact with stress to produce the observed memory effects. Future empirical research is needed to investigate the interaction of stress and arousal, with the use of objective measures, on subsequent memory performance and misinformation effects for aspects of an event that are not only emotional but that are also relevant to survival in a potentially life-threatening situation.

Second, manipulations typically used in laboratory settings to induce stress (e.g. TSST, cold-pressor task) and arousal (e.g. aversive materials) can only approximate stress and arousal responses experienced by an individual as they witness a crime. For real-world witnessed events, stress and arousal responses likely co-occur, are more extreme, and are induced by the event itself. This means that stress and arousal are interacting while an eyewitness event is being encoded, and that both are directly related to the to-be-remembered event. In the present design, arousal was induced using the to-be-remembered materials (i.e. the negatively arousing slideshow) while stress was induced prior to slideshow encoding through a completely separate event that was unrelated to the to-be-remembered materials. Thus one might imagine that in a real life-threatening situation the stress response may interact with arousal evoked by the aversive event somewhat differently than what was observed in the current study.

The third factor that should be considered is the method by which memory was tested. Typically, when witnesses are questioned they are asked open-ended questions and are free to report whatever comes to mind. In the current study, memory for the event was tested using a four-alternative forced choice recognition task during which participants were provided with four possible answers for each question. This means that for items that were misinformed, the correct and misinformed answer (along with incorrect responses) were presented simultaneously and available for the participant to choose from. While this form of testing allowed us to assess memory accuracy and misinformation effects for all phases of the slideshow (something that was not possible using a free recall test) it may not be entirely comparable to eyewitness questioning.

In the current study cortisol was measured as an objective biomarker of the stress response; however, this single measure failed to show correlations with memory accuracy or misinformation effects. One conceivable reason for this is that cortisol is a single component of a very complex physiological response that involves the release of a number of different hormones, including norepinephrine, that are known to influence processing in brain regions important for memory and emotional learning (i.e. hippocampus and amygdala). Under conditions of stress and arousal, cortisol and norepinephrine in particular appear to act synergistically to play an integral role in emotional memory enhancement effects (Roozendaal, Okuda, de Quervain, & McGaugh, 2006a; Roozendaal, Okuda, Van der Zee, & McGaugh, 2006b; Segal & Cahill, 2009). Under conditions of stress, where cortisol levels are presumably elevated, blockade of norepinephrine release (or administration of a noradrenergic antagonist) reduces functional activation in the amygdala (van Stegeren et al., 2005, 2007), and impairs memory for emotionally arousing materials (Maheu et al., 2004; van Stegeren et al., 2005, 2007). Thus while the examination of cortisol as an objective measure of the physiological stress response is clearly valid, an investigation of the relationship between cortisol and memory performance, in the absence of measuring its interaction with other stress hormones (e.g. norepinephrine) may be limited.

Aside from the above noted limitations, the current findings have interesting implications for understanding factors that moderate misinformation effects. One must consider the current findings in light of several of the prominent theoretical positions that have attempted to account for misinformation effects. The original view of the misinformation effect posited that it reflects the "overwriting" of memory for the original event by false information (Loftus 1979a,b; Loftus & Loftus, 1980). Our findings would suggest that the interaction of stress and arousal, elicited by the aversive eyewitness event, leads to a strengthened memory representation of the original episode that is subsequently more resistant to the incorporation of misinformation. A similar interpretation of our findings can be given with respect to a view of the misinformation effect arising from reconsolidation processes through which false information is integrated into the memory trace that represents the original event. The amygdala is known to modulate consolidation of memories for emotionally arousing experiences (see McGaugh, 2004, for review) and increases in amygdala activity after emotional arousal have been linked to enhanced consolidation of emotional memories (Pelletier, Likhtik, Filali, & Paré, 2005). Recent studies have provided evidence that emotional, compared to neutral, information is more resistant to updating (Nashiro, Sakaki, Huffman, & Mather, 2012a; Novak & Mather, 2007) and that this effect may depend, at least in part, on amygdala-driven processes that work to preserve the original memory representation (Nashiro, Sakaki, Nga, & Mather, 2012b; Sakaki, Niki, & Mather, 2011). Given this, it could be argued that consolidation of the original memory for the emotionally arousing story was strengthened via arousal- and stress-mediated processes, resulting in a memory trace subsequently more resistant to updating. Along these lines, one could postulate that resistance of emotional memory to updating (i.e. reconsolidation) may depend, at least in part, on state-dependent factors (Dudai, 2007). In other words, emotional memory traces may be more likely to undergo updating if arousal and physiological stress states match those experienced during encoding of the original event. Future research is needed to test these notions. Collectively, these positions imply that stress and arousal alter physiological conditions such that memory for emotional stimuli remains largely intact, as well as fairly accurate, despite post-event exposure to false information. Such a mechanism might ensure that an organism accurately remembers salient, and potentially dangerous, components of a life-threatening event so that future behaviors can be modified to increase chances of survival.

Other theoretical positions posit that misinformation endorsement reflects errors that arise from competition between neural traces, the original memory trace and the memory trace of false information exposure (see Ayers & Reder, 1998 for review). The memory trace that includes false information may be more likely to be endorsed during retrieval, partially as a function of it having been acquired more recently than the original event (for which the memory trace may be weaker or degraded) (Belli, Windschitl, McCarthy, & Winfrey, 1992). Stronger memory traces overcome those that are weak and misinformation effects arise. In light of our results it could be argued that the emotional memory trace for the original event is strengthened by the influence of stress and arousal, resulting in a stronger memory trace than that for the recently acquired false information. As a result, this information is recollected during retrieval over misinformation. Theoretical positions focused on source memory speculate that the misinformation effect may result from confusion regarding the source of the original event information and that of misinformation (i.e. source misattribution; Johnson, Hashtroudi, & Lindsay, 1993; Lindsey & Johnson, 1989). Such a theoretical position could account for the current results by claiming that the arousing nature of the negative slideshow, in combination with heightened physiological stress during encoding, results in the formation of a very distinct memory for the source of the original event. The source of the original event may be distinct simply as a function of its emotional content or alternatively as a function of stress- and arousal- mediated enhanced consolidation (e.g. see English & Nielson, 2010). Consequently, subsequent endorsement of false information received from a completely different, and less distinct source, is less probable.

Our data do not allow us to distinguish among these possibilities, and interpretation of our findings with respect to the above theories requires additional research. Clearly more research on interactions between stress, arousal, emotional content, and memory malleability is warranted given the relevance of these constructs to eyewitness testimony. Nonetheless, results of the current study do add a new constraint to future attempts to account for misinformation effects. Namely, stress and arousal at encoding interact to enhance memory for aversive aspects of a negative event such that this information is subsequently remembered with accuracy and less vulnerable to the incorporation of misinformation.

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