Changing memories by interference: The effect of emotional dimensions in reconsolidation of episodic memories

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Abstract

Episodes with an emotional component preoccupy memory formation and this advantage facilitates their preservation and mitigates the impact of interfering episodes. The present study examined the relation of the emotional dimensions of original and interfering episodes to the memory outcome, using a reconsolidation paradigm. In a between-subjects design, 102 healthy young adults were presented with an emotional or neutral image and learnt either an emotional or neutral story, respectively (day 1). On day 2, experimental groups were presented with an image of the opposite emotionality, reactivated the original story and learnt a story of the opposite emotionality. On day 3, experimental and control groups were tested for their memory on target and filler clues of the original story, and rated both stories for arousal and valence. Overall, there was evidence of interference on the long-term retention of target clues only for the neutral story (i.e. when the interfering story was emotional), and of filler clues for both types of stories. Moreover, individual target clue retention rates correlated with the arousal ratings for both the original neutral story and the interfering emotional story, while they were not related to arousal ratings for the original emotional story or the interfering neutral one.

Keywords: reconsolidation; interference; memory; emotion; arousal

Introduction

Formed memories can be changed through interference. A memory cue can reactivate the original memory and initiate the memory stage of reconsolidation, i.e. a roughly 6-hour period during which original memories are prone to interference in every-day life and in experimental settings (Schiller & Phelps, 2011). This observation has led to several, not always successful, experiments and theoretical discussions toward improving the definition and highlighting potential every day and clinical implications of this phenomenon (Lane, Ryan, Nadel, & Greenberg, 2015; Lee, Nader, & Schiller, 2017; Elsey, Van Ast, & Kindt, 2018). Specific crucial features of reconsolidation have been described, such as sensitivity to partial cues and prediction error, context dependency, and susceptibility to pharmacological interventions (Nader, Schafe, & Le Doux, 2000; Hupbach, Gomez, Hardt, & Nadel, 2007; Hupbach, Hardt, Gomez, & Nadel, 2008; Sinclair & Barense, 2018).

Interestingly, the emotional dimensions of the original and intervening memories have not been studied extensively as distinct parameters, even though emotional memories have been long known to markedly differ from neutral memories in both formation (encoding and consolidation) and retrieval (Labar & Cabeza, 2006; Talmi, 2013). It has been proposed that emotional events engage a dedicated brain network contributing to the formation of long-term emotional memories that are more easily accessible and more resistant to forgetting than emotionally neutral memories (Labar & Cabeza, 2006; Talmi, 2013; Yonelinas & Ritchey, 2015).

Arousal has been studied more extensively as the crucial attribute of emotional memories (Mather, 2007; Phelps & Sharot, 2008), although valence has also been considered in several studies (Kensinger, 2009). Despite extensive research on the memory properties of emotional events and, independently, on the cognitive underpinnings of reconsolidation, only one study, to our knowledge, has explored the

role of emotionality of the interfering material on memory reconsolidation (Strange, Kroes, Fan, & Dolan, 2010). Strange et al. (2010) have shown that post-reactivation interfering emotional material can impair later recall of the original memory, acknowledging that they did not explicitly model how the subjective arousal of interfering memories interacted with reconsolidation processing. There is ongoing debate about the processes that account for the impact of memories of events perceived as traumatic, upon the maintenance, clarity, and accuracy of previously registered episodic memories. Furthermore, the content of recollected real-life episodes can regulate mood and consequently affect emotional well-being (Grol, Vanlessen, & De Raedt, 2017; Fernandez, Ros, Sanchez-Reolid, Ricarte, & Latorre, 2020).

With this study, we aim to investigate the relation of the emotional dimensions of original and interfering episodic memories with the mnemonic outcome of a reconsolidation paradigm. On day 1, all participants were presented with either a neutral or emotional image while learning a short story of matching emotionality. On day 2, participants in the two experimental groups were asked to reactivate the learnt story through covert rehearsal while viewing an image of the opposite emotionality. Subsequently, they underwent the interference manipulation: they were asked to learn a story of emotionality that matched the emotionality of the image (opposite to that of the original story). The covert rehearsal of the original story (learnt on day 1) while viewing an image of the opposite emotionality, in combination with the learning of a matched story intended to maximize prediction error and therefore enhance cross-story interference during reconsolidation (Sinclair & Barense, 2019). To promote this process, the emotional and neutral stories were closely matched and certain memory clues ("targets") were selectively paired to correspond in syntax but to oppose in emotionality; to assess the perceived emotionality of the stories, participants rated both

stories in arousal and valence. On day 3, both experimental and control groups —i.e., groups not exposed to interference learning on day 2— were tested for memory of the original story.

The first hypothesis of the present study was that the long-term retention rate of target clues (on day 3) will be lower for the neutral story (Experimental Neutral group) than for the emotional story on day 3 (Experimental Emotional group) and for the neutral story without interference learning (Control Neutral group), reflecting the competition of interference learning of emotionally charged material with the originally learned neutral material (Hypothesis 1a). In contrast, we hypothesized that long-term target clue retention memory of the emotional story will not be significantly affected by interference learning of the neutral story on day 2 (i.e., that retention rates displayed by the Experimental Emotional and Control Emotional groups will be comparable; Hypothesis 1b). Concerning the relation of perceived emotionality of the original and interfering stories with target clue retention rates, we also hypothesized that the perceived arousal of the original stories will correlate with their subsequent recall (Hypothesis 2a). Lastly, we put forward the hypothesis that the perceived arousal of the interfering emotional story will correlate negatively with the target clue retention rates for the neutral original story (Hypothesis2b).

Materials and Methods

Participants

Participants were 102 adults (50 females; age: M=24.64, SD=5.52 years; educational level in years of school attendance: M= 15.43, SD=2.63). Inclusion criteria were age between 18 and 40 years old, Greek as native language, and no history of learning disabilities or psychiatric/neurological disorders. Data acquisition was completed in two

phases: the first 81 participants were randomly assigned to the four study groups and completed the study prior to the COVID-19 pandemic, while 21 additional participants were recruited and randomly assigned to the two control conditions during the COVID-19 pandemic (approximately 12 months later in order to address the reviewers' comments on the initial version of the manuscript). The final four study groups were comparable in terms of age, educational level, and gender (see Supplementary Table 1). They were reached through flyers and an announcement on social media sites and a local newspaper. The research protocol was approved by the ethics committees of the Universities of Nicosia (Cyprus) and Crete (Greece), and all participants signed an informed consent form approved by the ethics committee of the country of conduct. Participants were not monetarily compensated for their participation in this study.

Materials

Two short, voice-recorded stories, closely matched on number and average frequency of words as well as syntactic structure, were used in order to approximate everyday life situations and increase ecological validity (Cahill, Prins, Weber, & McGaugh, 1994; Kroes et al., 2014). The content of the one story was designed to be emotionally neutral, while the content of the other story was emotionally charged, in the sense that it was intended to provoke negative emotions to the participants (for more details about the stories, see Supplementary). Two images of a forest scene presented on a laptop screen prior to listening to each story served as contextual cues upon learning and reminder cues upon recall (on day 3). The valence of the image presented with each story was congruent with story valence (for more details about the images, see Supplementary).

Procedure

Participants in the two experimental groups took part in three sessions (learning on day 1, interference on day 2, and recall on day 3) whereas participants in the two control groups took part in only two sessions (learning on day 1 and recall on day 3; Table 1). On day 1, participants were informed about the content of the study and signed the consent form. They were first asked to look at an image on the computer screen for approximately 30 seconds and then to listen carefully to a recorded story in order to repeat it later out loud (and if possible, by using the same words; see Supplementary for learning criteria). The story was always congruent to the content of the image (e.g. neutral image-neutral story). On day 2, participants in the two experimental groups underwent the same learning procedure as on day 1 involving the image and story of the opposite emotionality. In addition, while perusing the image of day 2, they were asked to covertly recall the story of the first day (memory reactivation with prediction error element; Sinclair & Barense, 2019). Participants in the control groups were not asked to engage in special activity on day 2. On day 3 all participants were presented with the image they had been exposed to on day 1 and administered a free recall test of the story they had learnt on day 1. Coding criteria for items recalled on day 3 are detailed in Supplementary Material. Retention rates for target and filler clues were calculated by dividing the recall score of day 3 by the recall score achieved on the last learning trial of day 1.

Immediately following the learning procedure, participants were asked to rate the perceived valence and arousal of the story they were trained with on the Self-Assessment Manikin scale (SAM; please note that valence scale was presented in reverse order to that of the original scale; Lang, Greenwald, Bradley, & Hamm, 1993). Participants in the experimental groups were asked to provide the ratings immediately after the learning procedure on days 1 and 2; participants in the control groups rated the

first story directly after learning (day 1) and the second story after completing the recall of the first story (day 3). In the main analyses we used three variables: arousal ratings of the emotional story, arousal ratings of the neutral story, and emotional minus neutral story difference ratings on arousal (arousal difference score).

Statistical analyses

In preliminary analyses we assessed differences in arousal and valence ratings between the two stories across groups with two separate 2 (Emotional/Neutral story rating) x 4 (Control Emotional/Control Neutral/Experimental Emotional/Experimental Neutral groups) mixed-design analyses of variance (ANOVA).

To address the first hypothesis of the study, we compared retention rates for target memory clues with a 2 (Interference/No interference groups) x 2 (Emotional-first/Neutral-first groups) factorial analysis of covariance (ANCOVA) with individual arousal difference scores as a covariate. A significant interaction was further explored with post hoc Bonferroni pairwise comparisons between groups with the same covariate. Similar ANCOVAs were performed on filler retention rates and intrusions during recall on day 3.

The second hypothesis of the study was addressed through zero-order correlations between arousal ratings (for the neutral story and the emotional story) separately for each of the two experimental groups. Coefficients were evaluated at Bonferroni-corrected alpha = 0.0063. Similar analyses with valence ratings were also performed and presented in the Supplementary material.

Results

Arousal and valence ratings

Participants rated the emotional story as more arousing than the neutral story (M_{emo}= 6.00, *SE*=.23 vs. M_{neut}= 2.62, *SE*=.16, *F*(1,98)=122.72, *p*<.001, η^2=.556; see Supplementary Figure 1). There was no main effect nor interaction with group in arousal ratings [main effect of group: *F*(3,98)=2.108, *p*=.116; emotion by group interaction: *F*(3,98)=1.489, *p*=.222; for valence ratings, see Supplementary].

Memory performance as a function of interference

Recall of target clues. In support of Hypothesis 1, there was an interference by emotion interaction [*F*(1,97)=4.715, *p*=.032, η^2=.046; for full results, see Supplementary]. Post hoc pairwise tests revealed that retention rates were significantly lower in the Experimental Neutral as compared to the Experimental Emotional group ($M_{NeutExp}$= .71, *SE*=.03 vs. M_{EmoExp}= .89, *SE*=.03; *p*<.001; Figure 1a), corroborating Hypothesis 1a. The combined effect of memory interference and emotionality of the interfering story on subsequent retrieval was further attested by the significantly lower retention rates of the neutral story demonstrated by the Experimental Neutral group as compared to the retention rates of the Control neutral Group ($M_{NeutExp}$= .71, *SE*=.03 vs. $M_{NeutCon}$= .84, *SE*=.03; *p*=.032). The covariate-adjusted difference in target clue retention rates between the Experimental Emotional and Control Emotional groups did not approach significance (M_{EmoCon}= .88, *SE*=.03 vs. M_{EmoExp}= .89, *SE*=.03; *p*=1). Thus there was no effect of interference learning when the originally learnt story was emotional and the interfering one neutral, confirming Hypothesis 1b.

Recall of filler clues and intrusions. The specificity of the interference effect to those neutral story elements that competed with yoked emotional story elements was further supported by the lack of an interference by group interaction on filler clue retention

rates [$F(1,97)=.454$, $p=.502$]. Finally, there were no differences between emotional and neutral stories in the number of intrusions on day 3 [$F(1,52)=1.154$, $p=.288$; for full results, see Supplementary].

Memory performance as a function of perceived story arousal

In support of Hypothesis 2a, individual target clue retention rates of the neutral story by participants in the *Experimental-Neutral group* were significantly and positively correlated with arousal ratings for the original neutral story ($r = .532$, $p = .004$; Figure 1b). However, individual target clue retention rates of the emotional story by participants in the *Experimental-Emotional group* did not relate with arousal ratings for the original emotional story (Figure 1c & Supplementary Table 2).

In support of Hypothesis 2b, individual target clue retention rates of the neutral story by participants in the *Experimental-Neutral group* were negatively correlated with arousal ratings for the interfering emotional story ($r = -.504$, $p = .006$; Figure 1b), while there was no relation between individual target clue retention rates of the emotional original story and the arousal ratings for the interfering neutral story for the *Experimental-Emotional group* (Figure 1c & Supplementary Table 2).

Discussion

The main finding of the present study is that a negatively charged narrative learned soon after reactivation of a previously learned, emotionally neutral story impacts the reconsolidation of the latter, impairing subsequent recall capacity. Support to the study hypotheses highlights a number of relevant conclusions. Firstly, it appears that emotionally-charged material can interfere with the reconsolidation of emotionally-neutral material, while itself is more resistant to non-emotional interference. Furthermore, individual memory performance for the original story directly correlates

with the arousal ratings for the original neutral and the interfering emotional stories, while there were no correlations of that kind for the emotional story (with interfering neutral story).

Crucially, our findings reveal an emotionality by interference interaction on the retention rates for target memory clues, after controlling for individual differences in subjective arousal ratings between emotional and neutral stories. In particular, learning a new interfering emotional story after the reactivation of the original neutral story significantly decreased the recall of target clues from the original (neutral) story (confirming Hypothesis 1a); conversely, learning an interfering neutral story after the reactivation of the original emotional story did not affect the recall of target clues for the original emotional story (confirming Hypothesis 1b). As previous research has extensively showed that emotional stimuli are better remembered (for reviews, see: Buchanan, 2007; Talmi, 2013) but are also able to induce forgetting upon reconsolidation (Strange et al., 2010), this finding prompts the question: was the original emotional story better remembered and therefore less prone to interference, or was the interfering neutral memory less effective? Although our design cannot directly address this question, it seems probable that the two explanations complement each other in reconsolidation processing.

Interestingly, our finding that the target memory clue retention rates are not only positively correlated to the arousal ratings for the original neutral story but moreover negatively correlated to the arousal ratings for the interfering emotional story reinforces this viewpoint (in support of Hypotheses 2a and 2b for the Experimental Neutral group). However, there is no correlation between the target memory clue retention rates and the arousal ratings for the original emotional story and the intervening neutral story (disproving Hypotheses 2a and 2b for Experimental Emotional group). Taken together,

these results highlight an intriguing but not straightforward relation between arousal of the original and interfering stories and memory performance, which should be further examined in the future.

Importantly, it is unlikely that the aforementioned results are attributed to (i) individual differences in absolute perceived arousal (or valence) of the two stories, (ii) relative arousal (or valence) triggered by the two stories, or (iii) group differences in absolute or relative arousal/valence. Yet the emotional story was indeed perceived as more arousing and negative than the neutral story across participant groups. Past research has shown that arousal and valence ratings of that type may vary according to changes in the physiological measures of internal states, such as heart rate and skin conductance responses, and facial expressions (Lang et al., 1993). Therefore, we can assume that participants actually perceived and responded differently to the two stories as per study design.

The present study has certain limitations that should be considered. Firstly, a between-subjects design was adopted, in order to fully control for interferences between conditions (i.e. each participant was exposed only to one of the conditions), as reconsolidation processes are reportedly very sensitive to contextual cues, such as the place of the experiment and/or the experimenter (Hupbach et al., 2007; Hupbach et al., 2008). We attempted to control for individual differences in perceived emotionality of the two stories when performing group comparisons, but several other sources of individual differences potentially affecting reconsolidation were not controlled for. Nevertheless, a within-subject design would have allowed more direct comparisons and therefore inferences. As both approaches have strengths and limitations, future research could test our hypotheses with a within-subject design. Secondly, although emotionality of the original and the interfering story seem to affect to an extent the memory output

for the original story, our design does not allow to directly address specifics of that interaction. Future studies could further examine the potential interference of stimuli of congruent emotionality to the original stimuli, including a neutral-neutral (with original and interfering stories neutral) and an emotional-emotional (with original and interfering stories emotional) conditions. Moreover, future studies should ensure that reconsolidation actually takes place (as suggested by Elsey et al., 2018). Thus, two conditions of stimuli of congruent emotionality a condition entailing delayed induction of interference beyond purported 6-hour window, and complementary memory tests to ensure that the observed effects were not caused by temporary inaccessibility of original story elements or continuing interference of the emotional story elements with the recall of the originally learned neutral story elements. Furthermore, because of the different type of exposure to the second story between the experimental and control groups (learning vs. mere presentation, respectively), there might systematic differences in emotionality ratings which were not considered in the analyses.

Although premature to consider direct clinical implications, our findings contribute to the long-standing research on the impact of emotional memories on ongoing psychological processes. Whereas highly arousing events are known to be better remembered than less arousing episodes, it appears that they can also negatively impact maintenance of previously encoded, less arousing events. In real life, this phenomenon may apply to occasions where a current, emotionally arousing experience, reactivates the recollection of an older, conceptually and/or contextually similar, but less arousing episode. The capacity of the former to interfere with the reconsolidation of the latter could result in either distortion or suppression of specific elements of the original memory. To the extent that this process interferes with the recollection of past, non-negative life experiences (which has been found feasible via direct stress induction;

Schwabe & Wolf, 2010), it could contribute to a predominance of negatively charged (or even traumatic) ones in a person's consciousness. Given that recollected experiences are potent mood determinants (Grol et al., 2017; Fernandez et al., 2020), such arousing, negative experiences could, in principle, affect a person's current mood directly, as well indirectly through reconsolidation and interference with previous experiences.

Declaration of interest statement

None.

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Tables & Figures

Table 1. Experimental procedure.

Group	Day 1 (learning)	Day 2 (reconsolidation)	Day 3 (recall)
Experimental Emotional	Negatively-charged image and story	Neutral image and story	Negative image-Recall of negative story
Experimental Neutral	Neutral image and story	Negatively-charged image and story	Neutral image-Recall of neutral story
Control Emotional	Negatively-charged image and story		Negative image-Recall of negative story
Control Neutral	Neutral image and story		Neutral image-Recall of neutral story

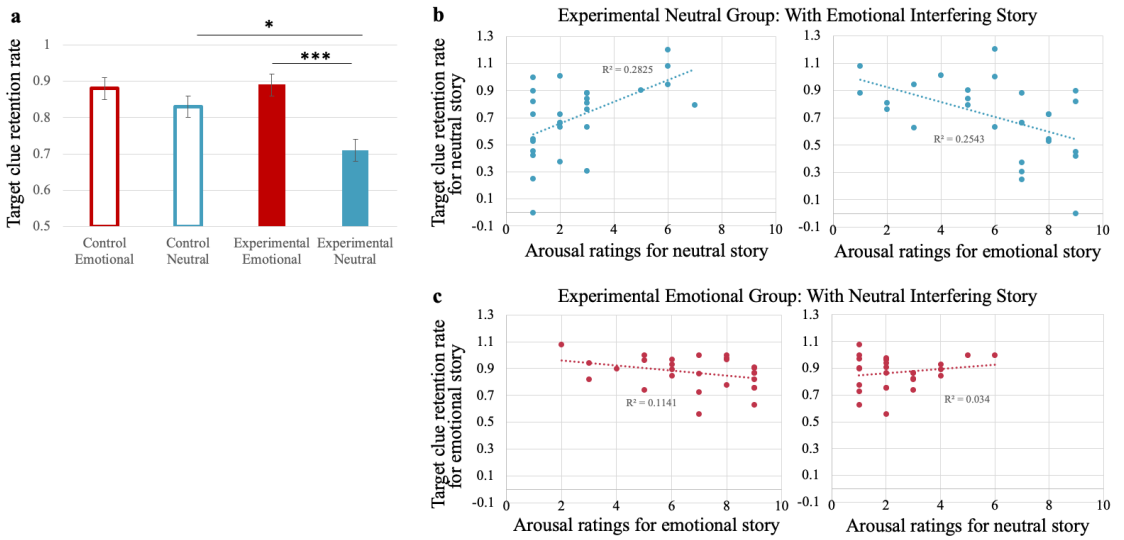

Figure 1. Memory performance (a) and its relation to arousal ratings (b-c).

(a) The learning of a new emotional story after reactivation suppressed the long-term retention rate of target clues from the original neutral story (experimental-neutral group), in comparison to the retention rate of target clues from the original emotional story (experimental-emotional story) when participants learnt a new neutral story after reactivation. Long-term retention for target clues did not differ between the control-

emotional and control-neutral groups. Values have been adjusted for individual differences in arousal ratings between conditions.

Error bars indicate SEM; *** $p \leq .01$ * $p \leq .05$.

(b) For the experimental neutral group, individual arousal ratings and target clue retention rates for the neutral story were positively correlated (upper left panel; $R^2 = .283$). Arousal ratings for the interfering emotional story correlated negatively with the target clue retention rates of the original neutral story (upper right panel; $R^2 = .254$).

(c) For the experimental emotional group, there were no significant correlations between the individual arousal ratings for the original emotional and the interfering neutral stories and the target clue retention rates for the original emotional story (lower panels; $R^2 = .114$ and $R^2 = .034$, respectively).