



Boosting long-term effects of degraded memories via acute stress

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ABSTRACT

Combining recall of an emotional memory with simultaneous horizontal eye movements (i.e., Recall + EM) reduces memory aversiveness. However, the long-term persistence of this effect is inconsistent across studies. Given that stress may aid in the consolidation of memories, we examined whether acute stress can boost the long-term effects of degraded memories. To test this, participants recalled two negative memories, which were assigned to a Recall + EM or Recall Only condition. Before and after each intervention they rated memory aversiveness (i.e., immediate effects) followed by a stress-induction or control procedure. After a 24h-period, participants rated each memory again (i.e., long-term effects). We found that Recall + EM produces immediate effects but that these effects dissolve over time. Moreover, acute stress did not boost potential long-term effects of Recall + EM. Degraded memories were not retained better by applying stress. We discuss these results and how long-term effectiveness may still be achieved.

1. Introduction

Eye Movement Desensitization and Reprocessing (EMDR) is a first-choice, evidence-based psychological treatment for posttraumatic stress disorder (PTSD; National Institute for Clinical Excellence, 2018; World Health Organization, 2013). A unique feature of EMDR therapy is that the patient makes horizontal eye movements by following the therapist's finger while simultaneously recalling a traumatic memory [1]. A corpus of lab-based dismantling studies investigating this dual-task procedure shows that combining recall of a negative autobiographical memory with simultaneous eye movements (i.e., Recall + EM) reduces self-reported vividness and emotionality of the memory compared to a Recall Only (control) condition without any eye movements (i.e., mere exposure; [2,3]).

One theory that has gained prominence in explaining why eye movements in EMDR are effective is working memory (WM) theory [4, 5]. According to this theory, both recalling a memory and making eye movements require WM resources. Because the combined execution of these two tasks require more resources than what the limited WM offers, competition arises [4,6,7]. As a result, the memory cannot be retrieved fully and is reduced in memory vividness and emotionality. Indeed, not only horizontal eye-movements, but any dual-task that induces

sufficient WM load can reduce the negative experience elicited by the memory [7,8]. However, how immediate effects of eye movements cascade into long-term effects and eventually into symptom reduction is still an empirical question [9,10]. It is possible that, due to the eye-movements, the memory is reappraised [4] or that the memory is reconsolidated in a degraded fashion into long-term memory [5].

Because lab-based dismantling studies have mainly focused on the immediate effects of eye movements, relatively little is known about the robustness of delayed or long-term effects of the dual-task intervention. Studies that did assess long-term effects (i.e., measured at least one day later) show inconsistent results. Some studies show that Recall + EM leads to clear reductions in vividness and emotionality compared to Recall Only [4,11]. Others show no change from the pre-test to follow-up for either condition [12,13] or find equal reductions in memory ratings in both conditions [14–18]. There is even one study that showed that the effects of Recall + EM are short-lived and relapse 24h later; thus showing larger reductions for Recall Only from pre-test to follow-up [19]. A meta-analysis on long-term effects indicates that reductions in memory ratings are indeed larger for Recall + EM compared to Recall Only, but only for memory emotionality (but not for memory vividness; [3]). This variability in long-term effects is a peculiar finding, because all studies (except [20]) show immediate effects with larger

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reductions for Recall + EM compared to Recall Only. Thus, the long-term effects of the dual-task intervention are inconsistent and are perhaps even fleeting.

For any immediate reductions in vividness and emotionality to last over time, the memories need to be permanently stored in long-term memory so that in future instances these changed memories will be retrieved. One possibility to boost the long-term effects of a degraded memory is by inducing acute stress. Previous studies have already shown that acute stress is involved in the immediate effects of the dual-tasking procedure; some level of arousal *during* the procedure is necessary to achieve reductions in vividness and emotionality [15,20]. However, how a memory is affected depends crucially on when stress is experienced [21–23]. For instance, experiencing stress after (re)learning generally improves consolidation of the memory [24–27]. Thus, it may be feasible to boost the long-term effects of the degraded memory by applying stress directly *after* the dual-task procedure.

Acute stress after a dual-task procedure would immediately reactivate the sympathetic nervous system with its release of (nor)adrenaline increasing heart rate and blood flow. After this quick response – about 15–20 min later – the hypothalamic-pituitary-adrenal (HPA) axis is maximally upregulated to produce glucocorticoids (cortisol in humans) [28,29]. Noradrenaline and glucocorticoids critically interact to enhance activity in brain areas involved in storage of emotional memory, such as the hippocampus and the amygdala [22,23]. As such, acute stress after a dual-task procedure may help the consolidation of the degraded memory and thereby strengthen the long-term effects of the intervention. Interestingly, the hippocampal and amygdaloid areas have also been implicated in the immediate effects of the dual-task procedure [30,31].

In the current study we investigated whether acute stress improves the long-term effects of emotional memories that were targeted via a dual-task procedure. To test this, participants recalled two negative autobiographical memories; one assigned to a Recall + EM condition the other to a Recall Only condition. Before and after each intervention they rated vividness, emotionality, difficulty, and distress of the targeted memory. Subsequently, participants either received a stress-induction procedure or a control procedure (i.e., Maastricht Acute Stress Test or MAST; [32]). Blood pressure and salivary cortisol were assessed at several points in the procedure to corroborate successful acute stress induction. After a 24h period, participants returned to the lab and again rated each memory. We expected to replicate previous work and show that Recall + EM reduces the negative experience elicited by the memory, and thus results in larger immediate decreases in memory ratings compared to Recall Only. Crucially, we hypothesized that the immediate reductions for the Recall + EM condition would be better retained (i.e., more robust over time; 24h later) when acute stress is applied after the Recall + EM procedure compared to when no stress is applied.

2. Method

2.1. Participants

Participants were recruited from research pools of Maastricht University. Participants could not participate when they reported (1) smoking more than five cigarettes a day, (2) drinking more than 5 units of alcohol a day, (3) using hard drugs, (4) being diagnosed or in treatment for stress-related psychopathology, or (5) having an endocrine disorder or cardiovascular problems. The final sample consisted of 59 participants ($M_{\text{age}} = 21.93$, $SD = 2.97$; 47 women, 12 men) carefully balanced over the Stress ($n = 29$) and No Stress ($n = 30$) groups. This study was approved by the Ethics Review Committee Psychology and Neuroscience at Maastricht University (ERC PN 175_05_04_2014 S2).

2.2. Measures

2.2.1. Memory characteristics

Emotionality was measured with the question, ‘how unpleasant (i.e., emotionally intense) is the memory for you at this moment?’. For vividness we asked, ‘How vivid (i.e., clear) is the memory for you at this moment?’. Difficulty of recall was assessed by answering, ‘How difficult is it for you to remember the memory at this moment?’.¹ All three questions were rated on a visual analogue scale with anchors 0 (*not at all*) and 100 (*extremely*). Subjective distress was assessed by asking, ‘How distressed are you at this moment?’ which was rated from 0 (*totally relaxed*) to 100 (*highest distress ever felt*) in increments of 10.

2.2.2. Cardiovascular and neuroendocrine stress responses

Systolic and diastolic blood pressure (SBP; DBP) were measured using an Omron 705IT (HEM-759-E; Omron Healthcare Europe BV, Hoofddorp, the Netherlands). This is a fully automated upper-arm oscillometric blood pressure monitoring device that is clinically validated by the Association for the Advancement of Medical Instruments, the European Society of Hypertension, and the British Hypertension Society (e.g., Refs. [33,34]). SBP and DBP were measured twice in succession at each time point and averaged into a single value for statistical analyses. Cortisol was assessed by taking saliva samples with synthetic Salivettes (Sarstedt®, Etten-Leur, the Netherlands). Samples were stored at $-20\text{ }^{\circ}\text{C}$ within 1 h of collection. Cortisol levels were determined by a commercially available luminescence immuno-assay (IBL, Hamburg, Germany).

2.3. Apparatus

2.3.1. Maastricht Acute Stress Test (MAST)

The MAST is a stress induction method that starts with a 5-min preparation phase followed by a 10-min acute stress phase [32]. The stress phase alternates hand immersion in cold water with mental arithmetic in a setting of unpredictability, uncontrollability, and social evaluation (i.e., negative feedback). In the preparation phase, participants were seated in front of a computer and were instructed about the upcoming task. They were explicitly informed that their facial expressions are recorded and that they need to immerse their hand in ice-cold water ($2\text{ }^{\circ}\text{C}$) multiple times. In between hand immersion trials participants had to count backwards from 2043 in steps of 17 as fast and accurate as possible. When they made a mistake, they received negative feedback from the experimenter and had to start over at 2043 (for the exact sequence and duration of hand immersion and backward counting intervals, see Ref. [32]). Participants in the control condition immersed their hand in body temperature ($36\text{ }^{\circ}\text{C}$) water and repeatedly counted from 1 to 25 in increments of 1 at a speed of their own choosing.

2.4. Procedure

After giving informed consent, participants were briefly screened (for a visual overview of the procedure see Fig. 1). After screening they were instructed to recall two vivid and emotionally negative autobiographical memories that were at least one day old. Participants graded both memories on unpleasantness and vividness by assigning a number to each memory (0 *not at all unpleasant/vivid* to 10 *very unpleasant/vivid*; [35]). A memory had to score at least 6 on vividness and 7 on

¹ In its current wording, “difficulty” is multi-interpretable and thus ambiguous because it can refer to both “cognitive effort” and to “emotional effort” (the latter partly overlapping with emotionality). Because of the ambiguous nature of this construct, we do not report on it further. Moreover, we recommend that in future studies difficulty should unambiguously be operationalized to solely reflect cognitive effort (e.g., “How effortful is it for you to remember the memory at this moment?”).

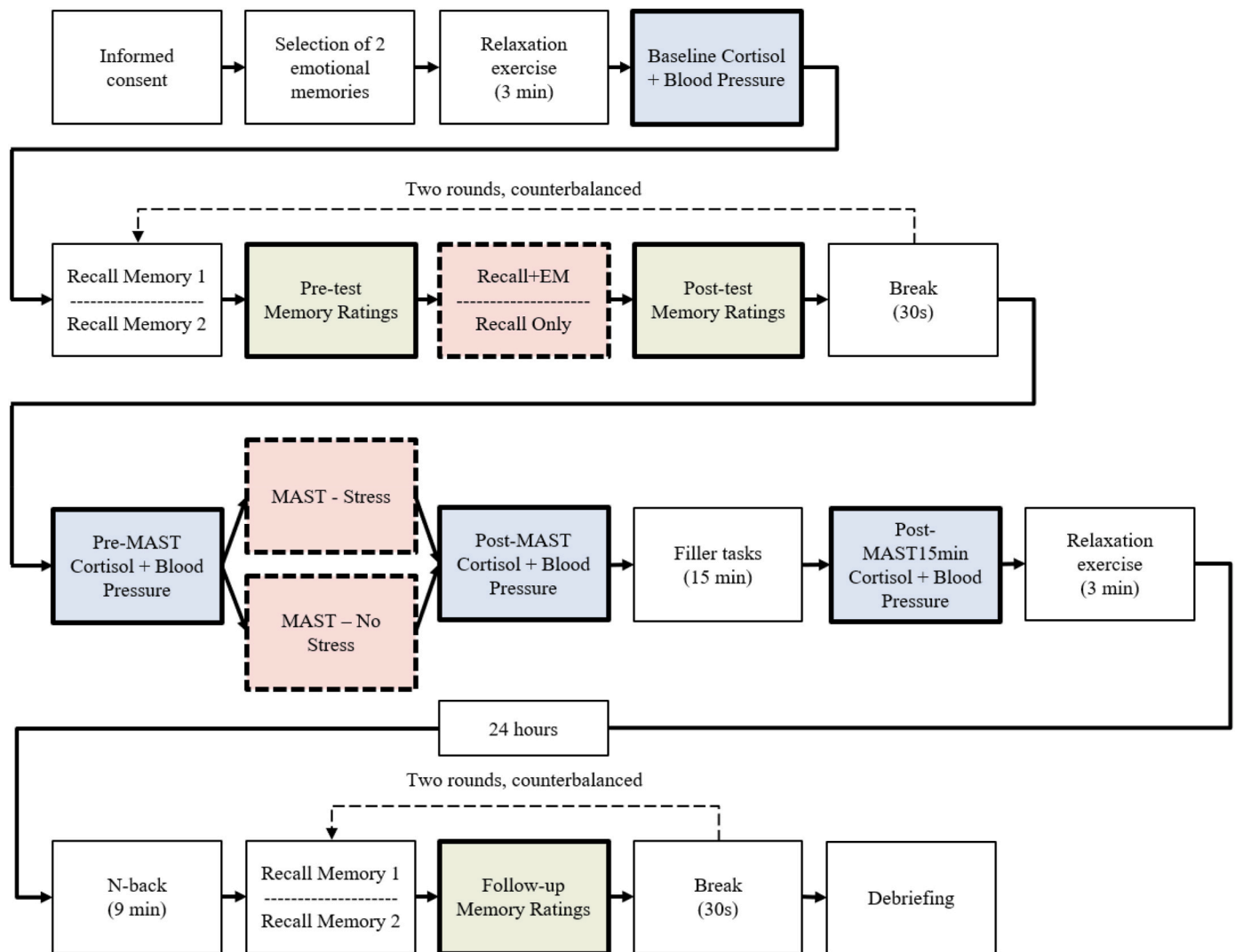


Fig. 1. Visual overview of the experimental procedure.

unpleasantness to be used in the study [35] when a memory was scored below one of these cut-offs the participant was requested to recall a new memory. If they had trouble in recalling these memories, participants were provided with a list of examples (e.g., involvement in an accident, emotional break-up). After two useable memories were selected, participants described each memory in general storylines and selected the memory hotspot that still evoked the strongest feelings of distress [1, 36]. Each memory hotspot was labeled with a brief neutral title, which served as a cue later in the experiment. After hotspot selection, participants engaged in a 3-min relaxation exercise in which they imagined being in a beautiful place while focusing on their breathing. Then, baseline cortisol and SBP/DBP measurements were taken.

Participants recalled the memory hotspot of one of the memories for 10 s and rated vividness, emotionality, difficulty, and distress. Then, participants were instructed to continuously recall their memory for 6 intervals of 24s (separated by 10s breaks) while tracking a white dot with their eyes that moved horizontally on the screen with a 1Hz speed (i.e., Recall + EM condition). At post-test, participants again rated vividness, emotionality, difficulty, and distress. Subsequently, they recalled and rated the other memory hotspot and then looked at a black screen (without a moving dot being present) while recalling the memory (i.e., Recall Only condition). Afterwards, they again provided post-test ratings on the four scales. Memory assignment to condition and the order of conditions in this phase was fully counterbalanced. At the end of

this phase there was a 30s break after which pre-MAST measurements of salivary cortisol and blood pressure were taken.

Then, depending on group assignment participants performed the stress-inducing MAST or the non-stress inducing control task. At the end of the intervention participants again provided a saliva sample and SBP/DBP was assessed. Subsequently, participants were instructed to fill out the State-Trait Anxiety Inventory-Trait Form (Spielberger, 1983) and the Symptom Checklist 90 (Derogatis et al., 1973). These questionnaires merely served as fillers until exactly 15 min had passed after the intervention ended. Participants were then briefly interrupted for a final saliva and blood pressure sample. After that they finished filling out the questionnaires. Day 1 ended with a 3-min relaxation exercise.

Participants returned to the lab 24h later and first performed a N-back task (results of which will not be described here). Subsequently, participants recalled the memory hotspot of one of the memories for 10 s and rated vividness, emotionality, difficulty, and distress. After a short 30s break they repeated the procedure for their other memory. The order of memory recall was counterbalanced over participants. At the end of the experiment participants were debriefed and reimbursed for their participation.

3. Results

All data were analyzed with JASP (2022, version 0.16.1). JASP is a

freely accessible, open-source package for statistical analyses. We report appropriate corrections in case of analysis-specific violations of assumptions. Data and associated analyses for this experiment have been made publicly available via the Open Science Framework and can be accessed at <https://osf.io/y4fna/>.

3.1. Immediate effects of dual-tasks

To replicate previous work on immediate effects, we focused on pre-to-post changes first for the Recall + EM and Recall Only conditions (i.e., factors Time and Condition). Because stress is induced after the dual-task procedure, the factor Group was not included in these analyses.²

For emotionality, there are main effects of Condition, $F(1, 58) = 16.837, p < .001, \eta_p^2 = .225$, and of Time, $F(1, 58) = 8.167, p = .006, \eta_p^2 = .123$. Importantly, these main effects were qualified by a Time \times Condition interaction, $F(1, 58) = 11.683, p = .001, \eta_p^2 = .168$, showing that scores for Recall + EM decline from pre to post-test, $t(113.626) = 4.455, p < .001$, while they remained stable for Recall Only, $t(113.626) = 0.717, p = .475$ (see Fig. 2, top panels for pre-to-post changes).

Vividness mirrors the effects for emotionality and again shows main effects for Condition, $F(1, 58) = 21.601, p < .001, \eta_p^2 = .271$, and Time, $F(1, 58) = 10.140, p = .002, \eta_p^2 = .149$. Crucially, Time and Condition interacted, $F(1, 58) = 40.413, p < .001, \eta_p^2 = .411$. Breakdown of this interaction shows that there was a decrease in scores for Recall + EM, $t(115.408) = 6.662, p < .001$, and an increase in scores for Recall Only, $t(115.408) = 2.000, p = .048$. Consequently, at post-test scores for Recall + EM are substantially lower compared to Recall Only, $t(97.133) = 7.306, p < .001$ (see Fig. 2, middle panels for pre-to-post changes).

Subjective distress again showed the familiar pattern with main effects of Time, $F(1, 58) = 56.275, p < .001, \eta_p^2 = .492$ and Condition, $F(1, 58) = 15.132, p < .001, \eta_p^2 = .207$, and a significant interaction of these factors, $F(1, 58) = 22.886, p < .001, \eta_p^2 = .283$. For subjective distress scores decline from pre to post-test both for Recall + EM, $t(112.612) = 8.822, p < .001$, and for Recall Only, $t(112.612) = 2.671, p = .009$. At post-test the scores for Recall + EM are lower than Recall Only, $t(106.556) = 5.968, p < .001$ (see Fig. 2, bottom panels for pre-to-post changes).

Overall, these analyses clearly show that Recall + EM (compared to Recall Only) results in substantial decreases in emotional memory characteristics. We thus replicate previous work on the immediate effects of making eye movements simultaneous with recall [2,3]. Replication of immediate reductions is crucial to test whether these are retained better by applying acute stress.

3.2. Effects of the stress manipulation

To check whether acute stress was successfully induced, we tested for changes in systolic blood pressure, diastolic blood pressure, and salivary cortisol in response to the MAST.

For systolic blood pressure the groups did not differ overall, $F(1, 56) = 1.785, p = .187, \eta_p^2 = .031$, though there was a main effect of Time, $F(3, 168) = 2.922, p = .036, \eta_p^2 = .050$. Importantly, there was a Group \times Time interaction effect, $F(3, 168) = 5.615, p = .001, \eta_p^2 = .091$, showing that systolic blood pressure was elevated for the Stress group compared to the no Stress group at post-MAST, $t(56) = 3.046, p = .002, d = 0.8$, but at none of the other timepoints, $ts(56) \leq 0.846, ps \geq .200, ds \leq 0.222$ (see Fig. 3, left panel).

Diastolic blood pressure showed a similar pattern compared to systolic blood pressure with a main effect of Time, $F(3, 168) = 5.506, p =$

.001, $\eta_p^2 = .090$ and a Group \times Time interaction effect, $F(3, 168) = 4.768, p = .003, \eta_p^2 = .078$, but no main effect of Group, $F(1, 56) = 0.012, p = .912, \eta_p^2 < .001$. Break-down of the interaction effect again showed that the Stress group displayed elevated blood pressure at post-MAST, $t(56) = 1.830, p = .036, d = 0.481$, and that the groups were comparable at all other timepoints, Welch's $ts \leq 1.543, ps \geq .613, ds \leq 0.405$ (see Fig. 3, middle panel).

Salivary cortisol data was first transformed to a natural logarithmic scale and then analyzed. There were no differences between the Stress and no Stress group overall, $F(1, 56) = 6.244, p = .112, \eta_p^2 = .044$, but there was an effect of Time, $F(1.88, 105.26) = 3.697, p < .031, \eta_p^2 = .062$, which was qualified by a significant Group \times Time interaction, $F(2.26, 105.26) = 19.948, p < .001, \eta_p^2 = .263$. Further inspection of this interaction showed – as expected – that the groups did not differ at baseline, $t(56) = 0.128, p = .449, d = 0.034$, and at pre-MAST, $t(55.89) = 0.668, p = .253, d = 0.176$, but that cortisol levels were increased for the Stress group at post-MAST, $t(56) = 1.959, p = .028, d = 0.514$, and at 15 min post-MAST, $t(56) = 3.142, p = .001, d = 0.825$ (see Fig. 3, right panel).

Taken together, these analyses on blood pressure and salivary cortisol show that the MAST was successful in eliciting cardiovascular and neuroendocrine stress responses. This can be taken as an indication that the Stress group indeed experienced acute stress on a physiological level.

3.3. Long-term effects of dual-tasks and stress

To test whether stress boosts long-term effects of decreases in emotional memory characteristics, we limited the analyses to posttest to follow-up measurements (i.e., the factor Time). We also included the factors Group (Stress vs. No Stress) and Condition (Recall + EM vs. Recall Only).

For emotionality we observed no evidence for main or interaction effects of Group, $F_s \leq 3.341, ps \geq .073$, showing that stress did not influence memory ratings for emotionality. We did observe a Time \times Condition interaction, $F(1, 57) = 7.581, p = .008, \eta_p^2 = .117$, that qualified the main effects of Time, $F(1, 57) = 4.219, p = .045, \eta_p^2 = .069$, and of Condition, $F(1, 57) = 25.725, p < .001, \eta_p^2 = .331$. Follow-up contrasts for this interaction show that Recall + EM remained stable from posttest to follow-up, $t(104.953) = 0.993, p = .323$, while Recall Only showed a steep decrease, $t(104.953) = -3.435, p < .001$. Conditions did not differ at follow-up, $t(113.442) = 1.833, p = .069$, suggesting that emotionality ratings converge over time irrespective of the manipulation employed (see Fig. 1, top panels for post-to-follow-up changes).

Vividness displayed a pattern similar to emotionality, with no main or interaction effects of Group, $F_s \leq 3.946, ps \geq .052$. Again, the main effects of Time, $F(1, 57) = 5.068, p = .028, \eta_p^2 = .082$, and of Condition, $F(1, 57) = 28.327, p < .001, \eta_p^2 = .332$, are better interpreted by the Time \times Condition interaction, $F(1, 57) = 21.461, p < .001, \eta_p^2 = .274$. Further break-down of this interaction showed that vividness increased from posttest to follow-up for Recall + EM, $t(103.035) = 2.466, p = .015$, while it decreased for Recall Only, $t(103.035) = -5.079, p < .001$. At follow-up there were no difference between conditions, $t(110.521) = 1.113, p = .268$ (see Fig. 1, middle panels for post-to-follow-up changes).

For subjective distress, experiencing acute stress did result in lower subjective distress for recalled memories overall, $F(1, 57) = 4.196, p < .045, \eta_p^2 = .069$, though this effect disappeared at follow-up as evidenced by a significant interaction with Time, $F(1, 57) = 6.376, p < .014, \eta_p^2 = .101$. However, the crucial three-way interaction with Condition was not significant, $F(1, 57) = 1.117, p = .295, \eta_p^2 = .019$, showing that there is no evidence that stress boosts storage of degraded memories. Just as for emotionality and vividness, Time and Condition did significantly interact, $F(1, 57) = 11.035, p = .002, \eta_p^2 = .162$. Further inspection shows this interaction was fully driven by an increase from posttest to follow-up for Recall + EM, $t(106.865) = 3.678, p < .001$, while scores

² For the sake of completeness, we also ran all analyses with the factor Group included and we did not find any significant two or three-way interactions with Time and/or Condition, $F_s \leq 2.482, ps \geq .121$ for any of the variables, nor did including Group change the interpretation of the reported analyses on immediate effects.

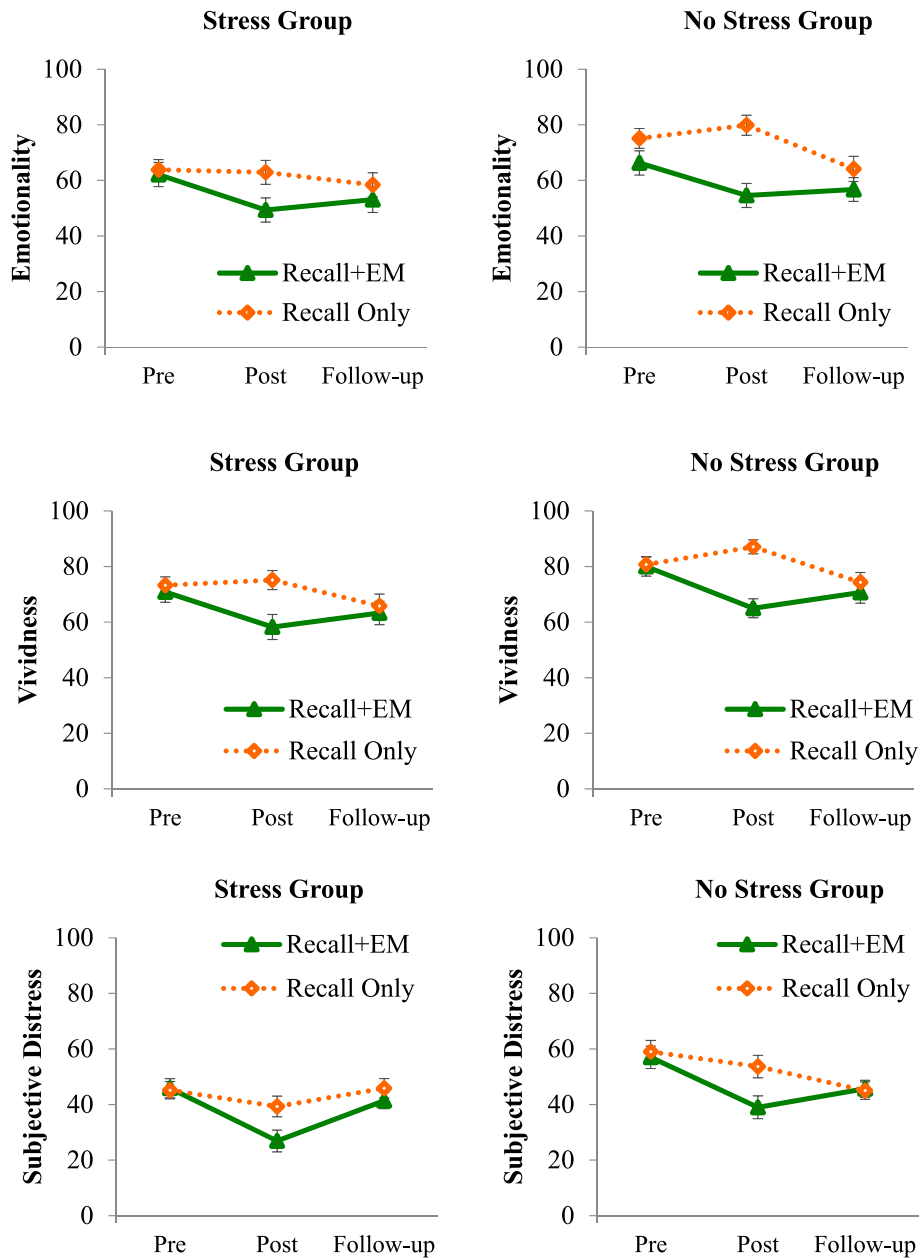


Fig. 2. Immediate Effects (Pre to Post) and Long-term Effects (Post to Follow-Up) in Emotionality (top two panels), Vividness (middle two panels), and Subjective Distress (bottom two panels) for the Stress and No Stress Groups (Means and Standard Errors are displayed).

for Recall Only remained stable, $t(106.865) = -0.368, p = .714$. In the end, at follow-up, both conditions showed similar scores on distress, $t(111.670) = 0.713, p = .477$ (see Fig. 1, bottom panels for post-to-follow-up changes).

Overall, these analyses show that there is no evidence that acute stress boosts the long-term effects of reductions in vividness, emotionality, and distress. One consistent finding in all these analyses is that both conditions converge at follow-up for all variables.

4. Discussion

The current study had a two-fold goal. First, we wanted to replicate previous work and show that Recall + EM degrades memory and thus results in larger immediate decreases in memory ratings compared to Recall Only. Second, we wanted to investigate whether acute stress boosts the long-term effects of emotional memories that were targeted via the Recall + EM dual-task procedure. We found clear evidence that

making eye movements during memory recall produces robust immediate effects, as evidenced by substantial reductions in emotionality, vividness, and subjective distress. However, adding stress to this procedure did not boost the long-term effects. Interestingly, though immediate memory-degrading effects resulting from the dual-task procedure were clearly present, these were notably absent in the long-term.

Our finding that a Recall + EM dual-task procedure decreases a memory’s emotionality, vividness, and distress aligns well with a large body of literature showing that dual-task interventions can change the negative experience elicited by emotional memories [2,3]. At this moment, the best supported explanation for these immediate effects is competition that arises from the taxation of limited WM resources [4,5]. In other words, simultaneously making EM or executing another dual-task within the confinement of WM, hampers the complete recall of an aversive memory. This partial recall results in experiencing the emotional memory in a degraded fashion immediately after the

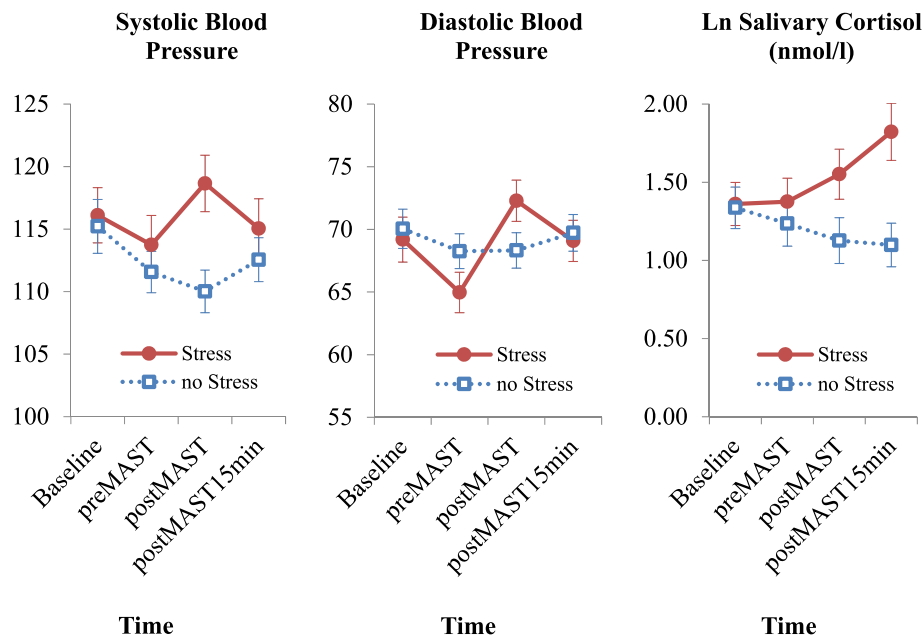


Fig. 3. Changes in Systolic Blood Pressure (right panel), Diastolic Blood Pressure (middle panel), and Salivary Cortisol (left panel) for the Stress and No Stress Groups (Means and Standard Errors are displayed).

intervention.

How these immediate effects become long-term effects is still a question that needs to be answered [9,10]. A possibility that we considered in the current study is that a degraded memory needs to be reconsolidated into long-term memory [5] and that experiencing acute stress would improve reconsolidation of that particular memory [24, 25]. This hypothesis is based on studies showing that experiencing stress after (re)learning generally improves storage of a memory [24–27]. However, although we successfully induced acute stress (as evidenced by increases in cardiovascular and neuroendocrine stress responses), this did not boost the long-term effects of immediate reductions in vividness, emotionality, and distress. In fact, the conditions (i.e., Recall + EM and Recall Only) converge at follow-up test (24h later) showing no added benefit from the dual-task procedure whatsoever, even though immediate effects were clearly present. These results converge with other studies in the literature, typically showing small differences between the Recall + EM and Recall Only conditions at delayed post-tests [3].

Why do these immediate effects in lab dismantling studies not manifest in the long-term? After all, in clinical practice EMDR is considered a first-choice, evidence-based psychological treatment for PTSD [50] and thus generally produces symptom improvement in the long run. A possible reason might be the relative short intervention duration in the laboratory (i.e., only 6 intervals of 24s in the current study). There are indications that (somewhat) longer interventions (i.e., 8 intervals of 24s) might be better, specifically for achieving long-term memory reductions [11], though there also is evidence contradicting this assumption. That is van Veen et al. (2020) used 32 intervals of 24s and showed that the effects of Recall + EM relapse 24h later, whereas memory ratings in the Recall Only condition showed a durable reduction at the follow-up test. Moreover, a meta-analysis shows that intervention duration (ranging from 2 to 45 min) does not affect the magnitude of immediate effects [3], which also casts doubt on the idea that intervention duration affects long-term effects (that is, assuming immediate effects are the basis for maintained memory degradation in the long-term).

It is still possible, however, that intervention duration is of importance for long-term effects, but that lab dismantling studies simply have gotten the design wrong to properly investigate this phenomenon.

Similar to EMDR treatment in clinical practice where multiple sessions are required to treat PTSD, achieving long-term effects in lab studies might simply require multiple (shorter) sessions on different days compared to one (prolonged) session on a single day. Multiple sessions may be essential given that the targeted autobiographical memories are rather robust against change because they are strongly encoded by emotional arousal and are strengthened over the years by repeated retrieval [37,38]. Thus, observing robust long-term effects for a dual-task intervention may only emerge when that intervention is spaced over multiple sessions. Re-storage of properly degraded memories might then still be boosted by stress induction.

In addition to the absence of long-term effects of the dual-task intervention, there may be different explanations for why we did not find that stress boosted the long-term effects of the intervention. We assumed that a dual-task procedure changes the original fear memory and that stress would then boost storage of this changed memory (i.e., reconsolidation; [5]). Because the memory's representation in long-term memory is modified, this should then limit the emotional response triggered by the memory when it is retrieved in a different context (see Davey, 1997). However, research does not always support this 'context-free' limited emotional response (e.g., Refs. [39–42]). Alternatively, it is possible that a dual-task procedure does not update the original unpleasant memory, but that it creates a new competing memory that inhibits the original unpleasant memory. This inhibitory learning theory is a common explanation for why exposure-based extinction is effective in Cognitive Behavioral Therapy [43]. Importantly, such an inhibitory competing memory might also be created in the Recall Only condition (which has strong parallels with imaginal exposure treatment; [44]). As such, if both the Recall + EM and Recall Only conditions are mechanistically identical, stress may affect these conditions similarly, which could explain the converging effects at follow-up. Indeed, there is evidence that stress and/or glucocorticoids may facilitate processes underlying exposure (such as extinction) [45, 46].

A common assumption of the reconsolidation and inhibitory learning theories is that the mechanism of action is related to the memory representation proper. However, another possibility is that the memory itself is not (or only minimally) changed. Instead, (temporary) reductions in memory ratings through a dual-task intervention may allow

individuals to relate differently to the memory (e.g., their perception of how dangerous the memory is; [4]). It may be that these changed beliefs and appraisals are stored alongside the memory and are the basis of long-lasting changes in memory aversiveness. Importantly, these changes in appraisal may be relatively unaffected by post-intervention stress induction. Surprisingly, memory appraisal has rarely been investigated in EMDR dismantling studies, although it is a crucial concept for the development and persistent of PTSD according to several trauma theories [47,48].

Several strengths and limitations of this study should be noted. Regarding strengths, the successful manipulation checks (i.e., of the dual-task intervention and stress induction) show that our manipulations have been successfully executed. As such, it seems unlikely that the lack of long-term effects of dual-tasks and stress are due to failed manipulations. Regarding limitations, the modest sample size of the study is worth bearing in mind. Post-hoc power calculations using G*Power indicated that for our sample size and based on a within-between subjects interaction in a repeated measures ANOVA with two groups and two measurement points (i.e., the long-term effect reflected in a post-follow-up difference score), statistical power was acceptable (i.e., .75) to excellent (i.e., 0.99) to detect effect sizes ranging from small-to-medium (i.e., Cohen's $f = 0.175$) to large (i.e., Cohen's $f = 0.4$). To detect small effect sizes (i.e., Cohen's $f = 0.1$), the statistical power of our study was low (i.e., 0.32). Nevertheless, the effects of stress manipulations and dual-task interventions are normally within the medium-to-large range [3,28,49]. Furthermore, our sample consisted of university students, which may restrict the generalization of our findings to other populations, though the processes at play (i.e., working memory, stress) are assumed to be universal cognitive processes.

In conclusion, we examined whether acute stress was able to boost the long-term persistence of immediate reductions in memory vividness, emotionality, and distress. Though we found that a dual-task procedure robustly produced immediate effects as observed by considerable decreases in emotionality, vividness, and subjective distress; long-term effects were absent even when stress was applied. To achieve and better understand long-term effects (and its potential interaction with stress) in lab-based EMDR studies, we propose moving away from single-session interventions and use interventions spaced over multiple sessions (on different days) and by focusing on the underexplored role of memory appraisal.

Author contributions

KvS: Conceptualization, Methodology, Formal analysis, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization.

MB: Investigation, Writing - Review & Editing.

SK: Investigation, Writing - Review & Editing.

GM: Conceptualization, Writing - Review & Editing.

TS: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing - Original Draft, Writing - Review & Editing, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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