



Shorter communication

## Intrusive memories: A mechanistic signature for emotional memory persistence

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### ABSTRACT

Memories of negative emotional events persist more over time relative to memories for neutral information. Such persistence has been attributed to heightened encoding and consolidation processes. However, reactivation of the encoded information may also lead to reduced memory decay through rehearsal or a reconsolidation processes. Here, we tested whether involuntary intrusive memories, spontaneously arising following a stressful event and reactivating its memory, function to prevent memory decay, enhancing its persistence. Participants watched a stressful film containing scenes of aversive material. Memory for the film contents was tested immediately post-film using a visual recognition test. In the following five days, participants recorded intrusive memories of the film using a digitized diary. After 5-days, memory for the film contents was retested. Results indicate that in the immediate aftermath of film watching, participant's memory scores were similarly high for scenes that were later experienced as intrusions and scenes that did not intrude, suggesting effective encoding for all scenes. However, persistence of memory for scenes that intruded was preserved relative to memory for scenes that did not intrude, pointing to a mechanism through which negative intrusive memories persist over time. Implications for memory modification interventions in trauma-related psychopathology are discussed.

### 1. Introduction

Memories of negative emotional events tend to persist over time, often remaining detailed and vivid (Brown & Kulik, 1977; Kensinger, Garoff-Eaton, & Schacter, 2006). Such memory persistence stands in contrast to memories of neutral events that typically decay over time. Persistence of memories of negative emotional events can be adaptive by guiding behavior in future similar circumstances. However, in some instances, persistence of negative memories can become maladaptive, as in the case of intrusive memories in post-traumatic stress disorder (PTSD), where memories of traumatic events continue to intrude involuntarily into consciousness, leading to substantial distress (American Psychiatric Association, 2013). Elucidating the mechanisms underlying persistence of negative emotional memories is therefore important both for basic cognitive science and for clinical psychopathology research. Here, we tested the hypothesis that involuntary intrusive memories, spontaneously arising following a stressful event, function to prevent memory decay. We applied a trauma film paradigm

and subsequently monitored intrusive memories of the film. Then, we contrasted visual recognition memory for intrusive relative to non-intrusive content.

Two stages of information processing have been proposed to influence persistence of emotional memories: encoding and consolidation. During encoding, emotional information receives privileged access to processing resources (Dolcos & Cabeza, 2002), elicits greater activation in specific emotion-related brain areas (Murty, Ritchey, Adcock, & LaBar, 2010), and receives greater attentional resources (Eastwood, Smilek, & Merikle, 2003; Fox, Russo, Bowles, & Dutton, 2001). Such effects during encoding could account for heightened memory of emotional relative to neutral information immediately following learning (Dolcos, LaBar, & Cabeza, 2004; Talmi, Schimmack, Paterson, & Moscovitch, 2007). During the consolidation window, a critical period for memory stabilization typically spanning several hours following encoding, varied factors can modulate the strength of the encoded information. For example, adrenal stress hormones (e.g., cortisol and epinephrine) are thought to modulate memory strength by influencing

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processes involved in memory consolidation (McGaugh, 2013), and amygdala connections with other brain regions can enhance encoding and consolidation of emotional memories (Phelps, 2004). In accord with the time-dependent nature of the consolidation process, studies have shown that memory advantage for emotional relative to neutral information emerges over time, while not present immediately following learning (Sharot & Phelps, 2004). Further, hyper-activation of emotion-related brain regions during encoding correlates with long-term, rather than short-term, memory performance (Cahill et al., 1996; Tabert et al., 2001), indicating that processes other than enhanced encoding are involved in the maintenance of emotional memories.

More recently, it has been proposed that modulation of memory strength may become possible following retrieval, during a limited time-window of memory reconsolidation. Under this framework, interference during the reconsolidation period can reduce memory strength (Kroes et al., 2014; Soeter & Kindt, 2011; Visser, Lau-Zhu, Henson, & Holmes, 2018). Alternatively, repeated reactivation of encoded information can lead to memory enhancement (Amar-Halper, Laor-Maayany, Nemni, Rosenblatt, & Censor, 2017; Monfils & Holmes, 2018; Oudiette, Antony, Creery, & Paller, 2013). In previous studies, memory reactivation was induced experimentally, using concrete reminders of the initially encoded event. However, in everyday life, memory reactivations are spontaneously occurring. In the case of negative emotional memories, reactivations of the stressful event may potentially occur every time an involuntary intrusive memory is experienced.

We test whether spontaneous intrusive retrievals of memories of the trauma film are related to memory decay over time. We expected that intrusive memories of particular film scenes would act to protect the intrusive content of that scene from memory decay, while memory for non-intrusive content will deteriorate over time. To differentiate between initial consolidation processes and reconsolidation involvement in memory persistence, we investigated whether intrusive memories experienced during the initial consolidation time-window (i.e. on the same day of film viewing) drive memory persistence, or whether intrusive memories emerging after the completion of the initial consolidation process (i.e. after a night of sleep, Smith, 1996) lead to memory persistence (Fischer, Hallschmid, Elsner, & Born, 2002; Stickgold, James, & Hobson, 2000; Walker & Stickgold, 2004). If intrusive memories experienced after the completion of this initial consolidation window lead to memory persistence, a reconsolidation account of emotional memory persistence would be supported. Alternatively, memory repetition accounts could explain such memory persistency (Sander, 1997; Ward & Tan, 2004). In addition, if memory intrusion is dependent upon heightened encoding, better memory for to-be intrusive items immediately following film watching is expected.

## 2. Methods

### 2.1. Participants

Twenty volunteers (10 females,  $M_{age} = 25.0$  years,  $SD = 4.6$ , Range = 18–40) were recruited through online and printed advertisements. Exclusion criteria were current self-reported neurological, physical, or mental disorders, and a score  $\geq 33$  in the posttraumatic stress disorder checklist for DSM-5 (PCL-5;  $M_{PCL} = 7.6$ ,  $SD = 7.9$ , Range = 0–27) (Blevins, Weathers, Davis, Witte, & Domino, 2015). Depression and trait anxiety were also assessed using the PHQ-9 (Spitzer, Kroenke, & Williams, 1999) and the STAI trait scale (Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983), respectively. These questionnaires indicated that the sample was on the non-clinical range ( $M_{PHQ-9} = 4.5$ ,  $SD = 2.7$ ,  $M_{STAI-T} = 35$ ,  $SD = 7.5$ ). Participants were informed that they are about to watch a film containing distressing content and that they could stop participation at any time. Participants provided written informed consent prior to testing, and compensated 40\$ for their participation. The Tel Aviv University Institutional Review Board approved the study (reference number:104.17).

### 2.2. Trauma film

The trauma film consisted of eight scenes displaying self-injury, eye surgery, documentation of animal cruelty, car accident, knee surgery, a scene of humans attacked by an animal, tooth extraction, and a man stabbed with a knife. Four of the scenes were taken from James et al. (2015) and the rest were selected for the present study. Average scene duration was 80.12 s ( $SD = 25.35$ ). The presentation of each scene was followed by a 2-min break, during which participants were requested to remain seated with their eyes closed until a sound signaled the beginning of the next scene. The eight film-clips were selected to contain different and specific contents to allow the later tracing of the specific intrusions reported in the digital diary and of the specific items on the recognition memory test (for a similar design see Clark, Holmes, Woolrich, & Mackay, 2016). Training in using the trauma film paradigm was received by NH from EH both remotely and through a lab visit.

### 2.3. Manipulation check

Before and after the trauma film participants rated how sad, scared, angry, and happy they felt “at this very moment” on a scale ranging from (0) “not at-all” to (10) “extremely”. A composite mood score (ranging from 0–40) was computed by summing all scales scores after inverting the happy scale score (Holmes, James, Kilford, & Deepprose, 2010). Further manipulation checks, conducted immediately following film watching, included ratings of attention paid to the film and distress experienced in response to each of the eight scenes from “not at all” (0) to “extremely” (10). Distress ratings were delivered using scenes title (e.g., ‘eye surgery’).

### 2.4. Reminder images

Reminder images were presented one day following film viewing and consisted of one neutral image from each of the eight scenes of the trauma film. The images served as reminder cues for scenes from the trauma film without re-exposing participants to its aversive content (James et al., 2015). Images were presented once at a time against a black background for 3 s, with 3 s inter-stimulus interval (ISI). The same eight reminder images were presented to all participants. The reminder images were different from the images used in the recognition memory tests.

### 2.5. Digitized intrusive memories diary

Participants recorded involuntary memories about the film in a digitized online diary accessible through their mobile phones (Qualtrics - version November 2017–July 2018, Provo, UT) that was developed for the current study. It was explained that intrusive memories come to mind unbidden (rather than deliberately recalled), and can arrive in the form of sensory mental images (e.g., sights and sounds from scenes in the film). A distinction was made between intrusive memories and pure verbal thoughts, which were explained to consist of thoughts in the form of words/verbal language relating to the film material without remembering any specific perceptual details. Verbal thoughts, when occurred alone, were not included in the intrusion analysis. Participants were requested to record any involuntary memory of the film immediately following its emergence, to indicate its type (mental image, verbal thought, or both) and describe its content in a way that would allow identification of the specific scene from which it emerged (e.g., car accident). Separate diary entries were requested for each intrusive memory, even if the same memory occurred more than once or if several memories intruded in succession. Participants were asked to provide diary entries at least three times per-day (morning, afternoon, and evening) even if they did not experience any intrusive memories, in which case a “no intrusive memory” option was entered in the diary. To match specific intrusions to one of the eight scenes in the trauma film, an

experimenter coded the written entry provided by participants into one of the eight scenes viewed (e.g., an entry “I saw the man being stabbed” would be coded as corresponding to scene number 8 in which a man was stabbed with a knife) or noted if they could not match the scene. The diary entries were coded by a second experimenter; inter-rater reliability was 97%.

2.6. Recognition memory test

To probe memory strength rather than retrieval accessibility, we used a two-alternative forced-choice recognition memory test (Davis, Sutherland, & Judd, 1961; Kintsch, 1968; Long, Danoff, & Kahana, 2015). Fig. 1B depicts the sequence of events in a single trial from the visual recognition memory test. The test consisted of three trials per-scene, yielding a total of 24 trials, each trial presented two images one after the other: one image was taken from the original film and the other depicted a similar content taken from another unviewed film. Pictures were presented on a 40 × 30-cm screen, with 1600 × 1200 resolution. Viewing distance was 80-cm. Each image was presented for 1000 ms with 1000 ms ISI. Trials were presented in a random order. After watching the two images, participants had to indicate as fast and accurate as possible whether the first or the second image was taken from the film. No time limit was imposed on responses. The next trial began following participants’ response. We used a 2-alternative forced-choice test to avoid possible response biases (liberal or conservative), to which other memory tests (e.g., old/new recognition memory test) are vulnerable to unless bias is measured and accounted for. A pilot study (n = 9) ensured lack of floor or ceiling effects in the current test immediately following film viewing (M = 83.1%, SD = 11.1) or five days later (M = 73.7%, SD = 13.6).

2.7. Procedure

Fig. 1. A reflects the study design. The experiment consisted of three lab visits on days 1, 2, and 5, and completion of a digitized online diary for 5 days (days 1–5). On day 1, participants received information about the study and provided written and informed consent. Participants then watched the trauma film alone in a darkened room using headphones with pre-determined volume for sound. The manipulation check was then administered, consisting of the four visual-analogue scales, attention and distress ratings. Then, participants completed the first recognition memory test (Fig. 1B). At the end of day 1, participants received detailed instructions on how to use the digitized diary and completed a checklist to ensure understanding of diary instructions. Participants were requested to sleep for at least 6 h on the following night (to encourage proper memory consolidation).

The second visit occurred the next day (day 2). Participants watched

neutral reminder images taken from the film watched on day 1. The same neutral image from each of the eight scenes was presented to all participants. Pilot data indicated that these memory reminders elicit a greater number of film-related intrusive memories that can last for five days following film viewing. Participants remained in the lab for another 10 min, during this time they completed a standardized music filler task (Holmes, Lang, & Shah, 2009). The filler task was used to ensure that the same conditions are met by all participants immediately following memory reminders, to enable memory reconsolidation and prevent from interfering tasks from lowering the impact of the reminder procedure.

Five days following the first study visit, participants arrived for the third and final visit (day 5). They completed the recognition memory test (Fig. 1B), and rated the accuracy of their diary completion on a scale ranging from “not at all accurate” (0) to “extremely accurate” (10). Finally, participants were debriefed and reimbursed for their participation.

2.8. Data analysis

The internal consistency of response times on the visual recognition memory tests (day 1 and day 5) was assessed using Cronbach’s alpha. To assess the influence of intruded vs. non-intruded content on memory for the film, scores in the recognition memory test were divided into scenes for which a participant experienced intrusive memories (1 or more), and scenes for which no intrusions were experienced. Due to high variability between individuals in the amount of intrusions experienced, we used a weighting procedure essential for the robustness and reliability of the data (Schluchter & Elashoff, 1990; Tibon & Levy, 2015). Since the number of intruded/non-intruded scenes and the number of intrusions experienced for each intruded scene were different across participants, scores in the memory test were weighted to account for this imbalanced data (see Supplementary Material for more information about the weighting procedure and for non-weighted and partially weighted results). This weighting process assured that scores determined by fewer trials in the memory test or by fewer intrusions would receive less weight. To account for the number of trials comprising the memory test, participants that had only one scene intruded/non-intruded received the lowest weight (1) whereas participants who had four intruded and four non-intruded scenes received the highest weight (4). The distribution of the number of scenes intruded was normal with a mean of 4.4 scenes intruded and a standard deviation of 2.1. To account for the number of intrusions experienced for each intruded scene, z-scores of the average number of intrusions were also used as weights, shifted above the zero to avoid negative values. The distribution of the average number of intrusions experienced per scene was approximately normal with a mean of 3.2 intrusions per scene and a standard deviation of 3.5. Two participants were excluded from these analyses because they reported

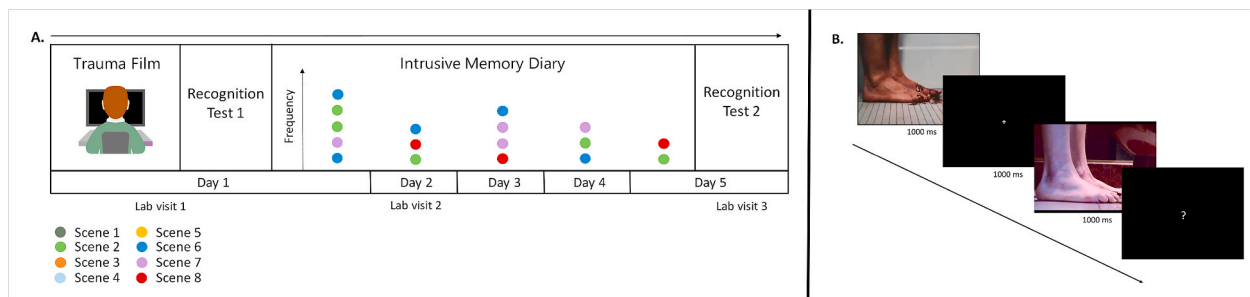


Fig. 1. A. Overview of study design. On day 1, participants watched a trauma film consisting of 8 different aversive scenes, represented here in different colored points. Participants then completed a recognition memory test for the 8 different scenes from the film (recognition test 1). Throughout the following five days, participants recorded each intrusive memory about the film in a digitized online diary, and the scenes from which the intrusions emerged were identified. On day 5, participants completed the recognition memory test again (recognition test 2). B. Recognition memory test design. Two still images were presented successively for 1000 ms each, with 1000 ms inter-stimulus interval (ISI). Following pictures presentation participants were requested to choose which of the two images was taken from the original film they watched on day 1.

intrusive memories from all eight scenes in the film (not allowing for a within-subject comparison between intruded and non-intruded scenes).

A two-way repeated measures ANOVA was calculated with time (test1\test2) and intrusiveness (intruded\non-intruded) as within-subject factors and weighted percent correct in the memory test as the dependent variable. Another two-way repeated measures ANOVA, with the same independent variables, was calculated with the weighted response times (RTs) in the memory test as the dependent variable. To ascertain that the observed effects are not derived by participants with excessive number of intrusions, an additional analysis was conducted after winsorizing the average number of intrusions by reassigning outliers (participants above 2 standard deviations from the mean) the nearest value that lies within the valid (non-outlying) distribution. This analysis reduced the influence of outliers while maintaining all data points (Onoz & Oguz, 2003).

To investigate whether memory persistence was driven solely by intrusive memories experienced during the initial consolidation window (on day 1), similar two-way repeated-measures ANOVAs were calculated incorporating only scenes that became intrusive from the second day onward (excluding from the analyses scenes that became intrusive on the same day of film watching). If the same results were to emerge from this secondary analysis, it should degrade the possibility that intrusive memories experienced during the first hours following film-watching drive all of the observed effects. Four participants were excluded from these analyses because all of their intrusive memories began on the first day, hindering the possibility of investigating whether intrusive memories experienced after the completion of the initial consolidation window lead to memory persistence.

To further investigate the consistency of the relation between intrusions and memory strength within participants, we also computed a within-subject Spearman correlation between  $\Delta$  memory for each of the eight scenes viewed (% correct in memory test 2 – test 1) and the frequency of intrusions for each viewed scene. In this analysis, positive correlation indicates that higher frequency of intrusions is correlated with higher memory stability for their associated scenes (see Supplementary Results). To investigate whether the frequency of pure verbal thoughts differed between intruded and non-intruded scenes, a paired *t*-test was computed (see Supplementary Results). All analyses were conducted using two-sided statistical tests.

### 3. Results

#### 3.1. Manipulation check and memory intrusion characteristics

Paired *t*-test on the composite score of the visual-analogue scales confirmed that mood became more negative from pre ( $M = 6.25$ ,  $SD = 3.98$ ) to post ( $M = 16.90$ ,  $SD = 8.79$ ) film viewing,  $t(19) = 5.48$ ,  $p = .00002$ ,  $d = 1.22$ . Attention paid to the film was rated high ( $M = 9.10$ ,  $SD = 0.96$ ,  $Range = 7-10$ ). Accuracy of diary completion was also rated high ( $M = 8.45$ ,  $SD = 0.99$ ,  $Range = 7-10$ ). All participants made at least one entry to the diary on each day of the study. Mean self-reported hours of sleep on the night between day 1 and day 2 was 6.8 ( $SD = 1.1$ ,  $Range = 4-8.5$ ). Two participants slept less than the requested 6 h (4 and 5 h, respectively). These participants had their number of intrusions within the normal range (<1 standard deviation from the mean) and were thus not excluded from the study. Subsequent analysis indicated that the memory statistical effects remained when excluding these two participants.

A chi-square goodness of fit test indicated that intrusive memories were evenly distributed across the eight scenes,  $\chi^2(7) = 7.25$ ,  $p = .40$ . Paired *t*-test of the distress ratings of each of the scenes, rated immediately following film watching (day 1), revealed that intruded scenes were rated as more distressing ( $M = 5.99$ ,  $SD = 0.50$ ) compared to non-intruded scenes ( $M = 4.23$ ,  $SD = 0.53$ ),  $t(17) = 3.30$ ,  $p = .004$ ,  $d = 0.77$  (Fig. 2).

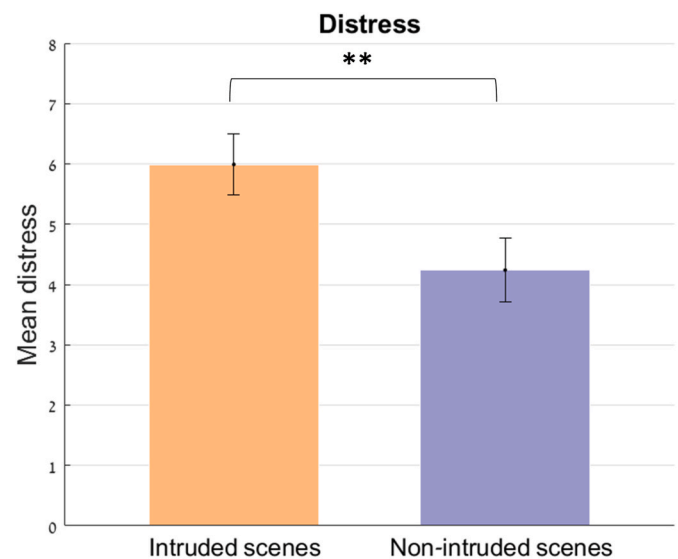


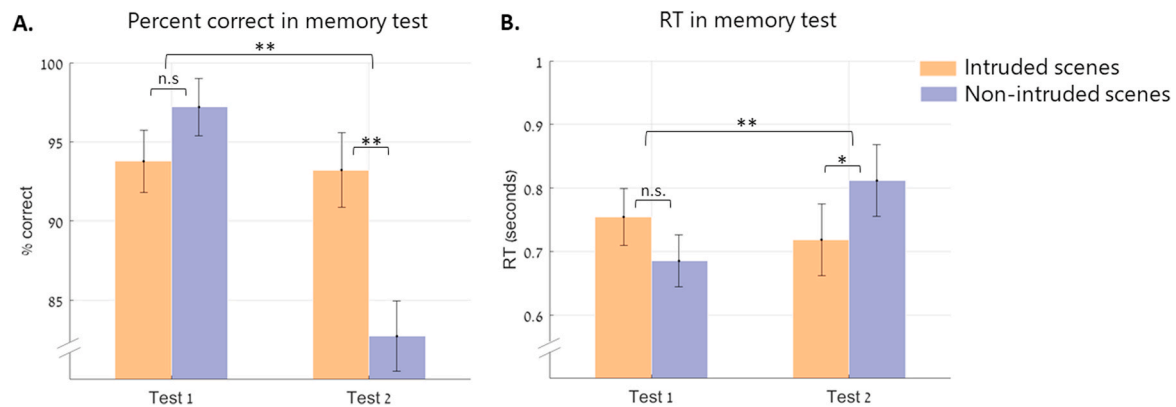
Fig. 2. Mean distress ratings (range 0–10) of intruded vs. non-intruded scenes. Scenes that intruded during the five days following film watching were rated by participants as more distressing compared to non-intruded scenes immediately after film watching. Error bars represent standard errors of the means.  $**p < .01$ .

#### 3.2. Memory

Internal consistency of the recognition memory test was high both for test at day 1 (Cronbach's  $\alpha = 0.837$ ) and test at day 5 (Cronbach's  $\alpha = 0.871$ ). The ANOVA on recognition memory scores revealed a main effect of time,  $F(1,17) = 15.13$ ,  $p = .001$ ,  $\eta^2_p = .35$ , with better memory in test1 ( $M = 95.4\%$ ,  $SD = 6.8$ ) compared to test2 ( $M = 87.9\%$ ,  $SD = 7.4$ ). This main effect was qualified by a time-by-intrusiveness interaction,  $F(1,17) = 23.05$ ,  $p = .0001$ ,  $\eta^2_p = .58$ . Follow-up contrasts revealed that on day 1 (Test1) memory scores for scenes that did not intrude ( $M = 97.2\%$ ,  $SD = 7.7$ ) were not different from memory scores for scenes that later intruded ( $M = 93.7\%$ ,  $SD = 8.3$ ),  $t(17) = 1.70$ ,  $p = .10$ ,  $d = 0.40$ . However, on day 5 (Test 2) memory scores for intruded scenes were higher ( $M = 93.2\%$ ,  $SD = 9.9$ ) compared to non-intruded scenes ( $M = 82.7\%$ ,  $SD = 9.4$ ),  $t(17) = 3.58$ ,  $p = .002$ ,  $d = 0.84$  (Fig. 3A). See Supplementary Material for partially weighted and non-weighted results.

The ANOVA on response times in the memory test revealed a time-by-intrusiveness interaction effect,  $F(1,17) = 21.24$ ,  $p = .0002$ ,  $\eta^2_p = .35$ . Follow-up contrasts indicated that while on test1 response times for scenes that did not intrude ( $M = 685$  ms,  $SD = 172$ ) were not significantly different from response times for scenes that later intruded ( $M = 754$  ms,  $SD = 191$ ),  $t(17) = 1.63$ ,  $p = .11$ ,  $d = 0.38$ , in test2 response times were significantly longer for non-intruding scenes ( $M = 811$  ms,  $SD = 238$ ) compared to intruding scenes ( $M = 718$  ms,  $SD = 240$ ),  $t(17) = 2.71$ ,  $p = .01$ ,  $d = 0.64$  (Fig. 3B). Main effects of time and intrusiveness were non-significant (all  $ps > .30$ ).

Following winsorizing to reduce the influence of outliers in the data, the statistical effects remained consistent both for recognition memory scores (time-by-intrusiveness interaction  $F(1,17) = 14.62$ ,  $p = .001$ ,  $\eta^2_p = .451$ ) and for response times (time-by-intrusiveness interaction:  $F(1,17) = 5.15$ ,  $p = .041$ ,  $\eta^2_p = .22$ ). A secondary analysis was conducted only for scenes that became intrusive from the second day on. This ANOVA on the memory scores revealed a main effect of time,  $F(1,15) = 5.99$ ,  $p = .027$ ,  $\eta^2_p = .28$ , with better memory in test1 ( $M = 94.9\%$ ,  $SD = 7.8$ ) compared to test2 ( $M = 88.2\%$ ,  $SD = 7.8$ ), which was qualified by a time-by-intrusiveness interaction,  $F(1,15) = 15.49$ ,  $p = .001$ ,  $\eta^2_p = .51$ . Follow-up contrasts revealed that while on test1 memory scores for scenes that did not intrude ( $M = 96.5\%$ ,  $SD = 8.9$ ) were not different



**Fig. 3.** Results of the recognition memory tests conducted on the first (Test1) and last (Test2) day of the study, divided to trials of scenes that intruded vs. not intruded throughout the 5-days period. **A.** Percent correct in the memory tests. Whereas memory scores were similar for to-be intruded and non-intruded scenes in Test 1, memory for intruded scenes was enhanced relative to non-intruded scenes in Test 2. **B.** Response times (RTs) in the memory tests. Whereas RTs were similar for to-be intruded and non-intruded scenes in Test 1, RTs for intruded scenes were lower compared to non-intruded scenes in Test 2. Error bars represent standard errors of the means. \* $p < .05$ , \*\* $p < .01$ .

from memory scores for scenes that later intruded ( $M = 93.4\%$ ,  $SD = 9.5$ ),  $t(15) = 1.28$ ,  $p = .21$ ,  $d = 0.32$ , in test2, memory scores of intruded items were higher ( $M = 93.6\%$ ,  $SD = 11.4$ ) compared to non-intruded scenes ( $M = 82.7\%$ ,  $SD = 9.0$ ),  $t(15) = 3.19$ ,  $p = .006$ ,  $d = 0.79$ .

In the ANOVA on response times for intrusion experienced from day 2 onward, no significant effect of time was found ( $F < 1$ ). However, there was a significant time-by-intrusiveness interaction,  $F(1,15) = 10.12$ ,  $p = .006$ ,  $\eta^2_p = .40$ . Follow-up contrasts showed that while on test1 response times for scenes that did not intrude ( $M = 701$  ms,  $SD = 169$ ) were not different from response times for intruding scenes ( $M = 762$  ms,  $SD = 191$ ),  $t(15) = 1.39$ ,  $p = .18$ ,  $d = 0.34$ , in test2, response times were longer for non-intruding scenes ( $M = 823$  ms,  $SD = 229$ ) compared to intruding scenes ( $M = 720$  ms,  $SD = 226$ ),  $t(15) = -2.87$ ,  $p = .01$ ,  $d = 0.71$ .

In the within-subject correlation between  $\Delta$  memory and intrusions frequency for each viewed scene, 77% of the participants showed a positive correlation, indicating that more intrusions were related to greater memory stability for their associated scene (see Supplementary Material, Fig. 2). Across participants, the mean correlation was significantly higher than zero ( $t(17) = 2.119$ ,  $p = .049$ ,  $d = 0.499$ ).

#### 4. Discussion

The findings of the present study provide evidence that stabilization of emotional memory is facilitated by spontaneous memory reactivations occurring in the form of intrusive memories. Intrusive memories were associated with preserved recognition memory for specific aversive contents over time, whereas memory of encoded scenes that did not intrude declined, suggesting that intrusions carry the capacity to considerably reduce normative memory decay over time.

Recognition memory for intruding compared with non-intruding scenes was similar immediately following film viewing, suggesting that all scenes have been efficiently encoded. Enhanced recognition memory for intrusive compared with non-intrusive scenes emerged only later, indicating that intrusive memories experienced over time are involved in memory (re)stabilization. Intrusive memories experienced outside of the presumed initial consolidation window (day 1) were also related to greater memory persistence, suggesting that downstream memory modification processes, beyond initial consolidation, are implicated in the dynamic nature of memory.

According to the reconsolidation framework hypothesis, reactivation of previously consolidated memories can lead to memory destabilization that necessitates new reconsolidation to persist (e.g. Monfils & Holmes, 2018). Manipulations during this reconsolidation time window have been shown to modulate memory strength (Kroes et al., 2014; Soeter &

Kindt, 2011). In the absence of a deliberate interfering manipulation, intrusive memories may simply function as repeated memory reactivations that in turn enhance via reconsolidation that memory's re-storage. Such processes can lead to preservation and persistence of memory. This interpretation is consistent with recent results indicating that intentional memory reactivations enhance basic visual perception, possibly due to reactivation-reconsolidation cycles (Amar-Halpert et al., 2017). However, system-level consolidation can occur over days or even months following encoding (Dudai, 2004), rendering the possibility that intrusions facilitate recognition memory through other processes than reconsolidation by influencing ongoing system-level consolidation processes. Alternatively, intrusions may function as rehearsal of the intruded scenes, leading to their mnemonic advantage. This interpretation of the results relies on theorists dating back to Ebbinghaus (Sander, 1997) and are in line with the proposal that rehearsal functions to offset the effects of memory decay (Brown, 1958). However, it is important to note that contrary to voluntary verbal rehearsal, as usually conveyed by these previous studies, our participants experienced spontaneous visual memory retrievals. It is possible that other forms of memory such as voluntary retrievals were also enhanced for the intruded scenes. Future studies could determine whether intrusive memories are also subject to higher voluntary retrieval, and whether such voluntary retrieval has similar effects on memory strength.

Whereas preservation of memory for negative emotional events has a clear adaptive function, some memories lead to maladaptive consequences as in the case of specific phobias or intrusive memories of a traumatic event in PTSD. Effective procedures designed to weaken intrusive negative memories depend on elucidation of the underlying processes involved. Whereas rehearsal accounts suggest that preventing rehearsal should lead to memory decay, memory reconsolidation accounts suggest that memory reactivation can be used as an opportunity for subsequent interventions designed to modify the memory trace. Correspondingly, previous experimental studies have incorporated memory reactivation procedures that initiate and then interfere with reconsolidation processes. Unlike lab-based experiments of memory reactivation, for patients with PTSD recurrent memory reactivations occur spontaneously in the form of intrusive memories that return vividly to mind (Bar-Haim et al., In Press; Hackmann, Ehlers, Speckens, & Clark, 2004; Iyadurai et al., 2019). Without being followed by processes that attenuate the reconsolidation process, the intrusive content of the trauma is likely to become highly persistent (Elsay & Kindt, 2017; Treanor, Brown, Rissman, & Craske, 2017). Development of effective procedures to interfere with reconsolidation processes shortly following memory intrusions in real life could facilitate innovations in the treatment of PTSD. Importantly, in the current study we did not manipulate

participant's behavior following their intrusions, allowing for high between-subjects variability that might have led to underestimation of intrusions' influence over visual memory stabilization.

While all participants in the present study were exposed to the same distressing film material, participants experienced intrusive memories of divergent scenes and consequently retained different information in memory. Participants' subjective distress ratings indicate that scenes experienced as more distressing were more likely to become intrusive, corresponding with current models of intrusive memories in PTSD (Brewin, Gregory, Lipton, & Burgess, 2010; Ehlers & Clark, 2000) and consistent with some lab-based findings (Clark, Mackay, & Holmes, 2015). Stress hormones at the time of encoding or memory consolidation have been reported to play a role in intrusive memories development (Bryant, McGrath, & Felmingham, 2013), suggesting interconnections between encoding, consolidation, and reconsolidation processes in the maintenance of emotional memory. Stress hormones were also found to strengthen the memory reconsolidation process (Bos, Schuijjer, Lodestijn, Beckers, & Kindt, 2014; Cocoz, Maldonado, & Delorenzi, 2011; Meir Drexler, Merz, Hamacher-Dang, Tegenthoff, & Wolf, 2015). It is likely that intrusive memories are accompanied by secretion of stress hormones, which possibly enhance the reconsolidation of the trauma memory and can lead to its enhanced stabilization.

The results of the current study should be viewed in light of some limitations. First, this study used an analogue of traumatic events to produce negative emotional memories. While the trauma film paradigm supplies a platform for experimental questions that are difficult to test on clinical samples and has been shown to induce intrusive memories over periods of days (James et al., 2016), the generalizability of the current findings to real-life traumas and to clinical populations remain to be further investigated. Furthermore, participants in this study were exposed to reminder images one day following film viewing to induce a sufficient amount of intrusions in this non-clinical sample, and were requested to fill in a diary, a task that could potentially prime intrusions. Exposure to deliberate cues of the event usually do not occur in real life, where reminders of the traumatic event are only spontaneously present, thus lowering the ecological validity of our study. Second, we measured memory strength using one form of visual recognition memory test. We selected this type of test because intrusive memories are most commonly experienced as visual imagery of the aversive event (Ehlers et al., 2002), but further tests could be used (Lau-Zhu, Henson, & Holmes, 2019). It remains to be determined whether other sensory modalities of memory are similarly preserved by memory intrusions. Third, and related to the previous limitation, in the present study we applied a forced-choice memory recognition test rather than other types of memory tests (e.g., free-recall). Memory recognition has the advantage of being more sensitive to memory strength and less influenced by retrieval dynamics (Kintsch, 1968; Long et al., 2015). However, the higher memory performance that is commonly seen in memory recognition relative to free-recall (Anderson & Bower, 1972; Davis et al., 1961) might have reduced detection of more subtle memory differences immediately following encoding. The future use of other memory tests can potentially detect more refined differences in memory strength immediately following encoding and elucidate the way in which other memory aspects, such as memory accessibility, are shaped by intrusions. Fourth, previous studies showed that sleep has a critical role in modulating emotional memories (Cox et al., 2018; Menz et al., 2013; Payne, Stickgold, Swanberg, & Kensinger, 2008; van der Helm et al., 2011). Future studies could directly address the role of sleep in visual memory stabilization as a function of intrusions using methods such as sleep polysomnography or sleep actigraphy (Porcheret et al., 2019). Finally, this was the first study to our knowledge to investigate the effect of spontaneous intrusive memories on visual recognition memory in a non-clinical sample. Therefore, tests of replication of this effect are warranted.

In summary, we demonstrated that intrusive memories of an emotional film are related to enhanced persistence of visual memory.

These findings point to the potentially adaptive function of naturally occurring memory reactivations in protecting negative memory from normal decay. Conversely, such mechanisms have implications for clinical populations for whom memory for a negative emotional event may continue to adversely affect their wellbeing and for whom the persistence of intrusive memories may be maladaptive.

### Author contributions

N.H. conducted the experiment, analyzed the data and wrote the manuscript. All authors were involved in study design, discussed the results and edited the manuscript.

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EAH reports formerly serving as an Associate Editor of Behavior Research and Therapy for which she received a honorarium.

EAH is on the Editorial Advisory Board of The Lancet Psychiatry. She is the F1000 prime: Clinical Psychology and Psychopathology Section Head and is on the Editorial Board of following journals: Current Opinion in Psychology, Clinical Psychology in Europe, Psychological Science and Cognitive Behavior Therapy. She receives no remuneration for these roles.

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EAH receives book royalties from Oxford University Press (Imagery and Cognitive Therapy) and Guilford Press (Imagery-Based Cognitive Therapy for Bipolar Disorder and Mood Instability). She receives occasional fees from clinical workshops and conference keynotes. She receives occasional consultancy fees from SBU: Statens beredning för medicinsk och social utvärdering.

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### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.brat.2020.103752>.

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