nature human behaviour

Article

https://doi.org/10.1038/s41562-024-01956-y

A systematic review and meta-analysis of experimental methods for modulating intrusive memories following lab-analogue trauma exposure in non-clinical populations

Received: 23 August 2023

Accepted: 15 July 2024

Published online: 21 August 2024

Check for updates

Mohith M. Varma^{1,2,11}, Shengzi Zeng^{2,3,4,5,11}, Laura Singh^{6,7}, Emily A. Holmes \mathbb{O}^8 , Jingyun Huang⁹, Man Hey Chiu² & Xiaoqing Hu $\mathbb{O}^{2,3,10}$

Experiencing trauma leads to intrusive memories (IMs), a hallmark symptom of post-traumatic stress disorder (PTSD), which also occurs transdiagnostically. Understanding why IMs increase or decrease is pivotal in developing interventions to support mental health. In this preregistered meta-analysis (PROSPERO: CRD42021224835), we included 134 articles (131 techniques, 606 effect sizes and 12,074 non-clinical participants) to investigate how experimental techniques alter IM frequency, intrusion-related distress and symptoms arising from lab-analogue trauma exposure. Eligible articles were identified by searching eight databases until 12 December 2023. To test potential publication biases, we employed methods including Egger's test and three-parameter selection models. We employed three-level multilevel modelling and meta-regressions to examine whether and how experimental techniques would modulate IM frequency and associated outcomes. Results showed that techniques (behavioural, pharmacological, neuromodulation) significantly reduced intrusion frequency (g = 0.16, 95% confidence interval [0.09, 0.23]). Notably, techniques aimed to reduce IMs also ameliorated intrusion-related distress and symptoms, while techniques that increased IMs exacerbated these related outcomes, thus highlighting IM's centrality in PTSD-like symptoms. Techniques tapping into mental imagery processing (for example, trauma reminder followed by playing Tetris) reduced intrusions when administered immediately after, or at a delayed time after trauma. Although our meta-analysis is limited to symptoms induced by lab-analogue trauma exposure, some lab-based results have now generalized to real-world trauma and IMs, highlighting the promising utility of lab-analogue trauma paradigms for intervention development.

A full list of affiliations appears at the end of the paper. Ze-mail: xiaoqinghu@hku.hk

Psychological trauma, defined as 'exposure to actual or threatened death, serious injury, or sexual violence'¹, impacts approximately half of the global population at least once in their lifetime². Experiencing trauma can lead to recurrent involuntary intrusions, referred to as intrusive memories (IMs), characterized by fragmented sensory episodes from the trauma, sometimes colloquially called 'flashbacks'^{1,3–6}. These intrusions, accompanied by emotional distress, can exacerbate a spectrum of symptoms associated with post-traumatic stress disorder (PTSD), such as avoidance and hyperarousal, thereby further deteriorating mental health and incurring staggering economic cost^{6–9}. For example, in the United States alone, the total economic burden of PTSD was estimated to be US\$232.2 million in 2018¹⁰.

Network models suggested that for PTSD patients, IMs were among the most central symptoms¹¹⁻¹³. While symptom centrality does not always directly translate into clinical relevance¹⁴, targeting IMs could be valuable given that they are distressing in themselves and impair peoples' daily functioning⁵. This opens an intriguing question of whether techniques that reduce intrusions could also alleviate intrusion-related distress and symptoms¹⁵, ultimately ameliorating PTSD symptoms.

The overarching goal of our preregistered meta-analysis is to examine the effectiveness of experimental techniques in modulating IMs, including intrusion frequency, intrusion-related emotional distress and symptoms (for example, sleep difficulties, emotional reactions) following lab-analogue trauma exposure among non-clinical populations. Achieving this goal can illuminate the mechanisms involved in the formation, perpetuation and alteration of IMs, paving the way for enhancing existing or developing new clinical interventions aimed at treating IMs and related symptoms. This knowledge will be valuable in supporting individuals to maintain mental health and resilience in the face of life adversity and trauma.

A plethora of experimental techniques have been studied in the laboratory for their effectiveness in modulating IMs^{5,6,16-19} (Fig. 1). However, a comprehensive quantitative examination of lab-based intrusion modulation techniques has yet to be conducted. Notably, these techniques encompass a wide spectrum, ranging from behavioural (for example, cognitive, emotional, social), to pharmacological (for example, oxytocin, alcohol) and neuromodulatory (non-invasive, transcranial electrical/magnetic stimulation) manipulations. Moreover, certain techniques aim to reduce or increase IMs, whereas others target modulating associated emotional distress and intrusion-related symptoms²⁰⁻²². While recent meta-analyses have examined the modulation of IMs²³⁻²⁶, they have either focused on specific subsets of techniques (for example, sleep, cognitive techniques), or only examined selected intrusion-related outcomes (for example, frequency only). Thus, a comprehensive examination of existing intrusion modulation techniques and their impacts on intrusion-related distress/symptoms would be both valuable and timely.

To induce IMs and related symptoms among non-clinical populations, researchers often use the lab-analogue trauma paradigms that employ film clips, sounds, pictures or immersive virtual reality (VR) depicting traumatic events (for example, severe injury, death or dying)^{5,16-18}. Although lab-analogue trauma exposure clearly deviates from real-world trauma exposure, viewing materials depicting traumatic events (such as real-world trauma in news media) nevertheless can elicit analogous responses such as intrusions or hyperarousal dimensionally akin to PTSD-like symptoms^{17,27,28}. Furthermore, according to the Diagnostic and Statistical Manual of Mental Disorders, fifth edition (DSM-5), actual PTSD symptoms can develop from trauma 'exposure through electronic media, television, movies, or pictures' when this exposure is 'work related'1 (for example, police viewing film footage of a murder). This suggests that at least in some circumstances, trauma exposure via viewing film footage can lead to clinical post-traumatic stress symptoms.

Our preregistered meta-analysis aimed to achieve the following goals. First, we aimed to examine the overall effect sizes for techniques that modulate intrusion frequency, intrusion-related distress and symptoms. Moreover, by examining intrusion frequency across various measures (that is, daily diaries, lab tasks or self-report questionnaires), we sought to determine whether different measures would converge in assessing the effectiveness of various techqniues²⁹.

Second, we aimed to provide procedural and mechanistic insights on which categories of techniques are effective and why they are effective. According to the procedure of a technique, we categorized individual techniques into three types: (1) behavioural, (2) pharmacological and (3) neuromodulation. In terms of mechanisms underlying IMs, both the dual-representation account (DRA) and the cognitive theory of PTSD^{9,30} propose that IMs arise due to excessive encoding of low-level sensory details of the trauma in conjunction with inadequate encoding of high-level verbally accessible components about the trauma^{3,7,8,31}. Accordingly, to modulate IMs, techniques can tap into imagery/visuospatial processing or verbal-conceptual (for example, elaboration/ contextualization) processing. More recently, the retrieval-based feedback loop model emphasized that the associated distress and negative appraisal accompanying maladaptive memory retrieval, such as involuntary intrusions, contribute to the persistence of IMs¹⁹. Therefore, techniques that reduce distress or change emotional processing could also potentially modulate IMs. Drawing from these theoretical frameworks that shed light on the mechanisms behind IMs, we further coded behavioural techniques into three major mechanistic categories: (1) imagery, (2) verbal and (3) emotional (see Fig. 2 for coding schema).

Third, we aimed to examine the timing of techniques being administered and when they are effective. Techniques can be administered either before, during/peri, immediately after the analogue trauma or even with a delay after trauma. Pre-trauma techniques might prove valuable for safeguarding certain professions that anticipate traumatic experiences (for example, firefighters). However, given the unpredictability of real-world trauma, post-trauma techniques, especially those effective even with a delay, may be more practical. Relatedly, neuroscientific evidence suggests that older memories are not fixed but can be updated when memory traces are reactivated³²⁻³⁷. This has prompted small-scale research into reducing long-standing intrusive memories in clinical cases of PTSD stemming from trauma many years ago³⁸⁻⁴⁰. In the current meta-analysis, within each timepoint of administration, we examined the moderation effects of Procedure- and Mechanism-relevant superordinate categories, and the effectiveness of individual techniques (for example, Trauma Reminder + Tetris, Positive vs Negative Cognitive Bias Modification (CBM), Sleep) in modulating IMs.

Compared with existing meta-analyses that focused on specific techniques in intrusion reduction²³⁻²⁶, the present meta-analysis provides presumably the most comprehensive examination so far by covering 131 unique techniques aimed at modulating IMs and intrusion-related outcomes (for example, intrusion-related distress and symptoms). To facilitate future research synthesis and empirical studies, we developed a website utilizing the meta-analysis dataset, allowing researchers to analyse the data freely and interactively (https://intrusivememory.shinyapps.io/shinymeta/).

Results

Description of included experiments

This meta-analysis included 134 articles, with n = 153 experiments, k = 606 effect sizes from N = 12,074 participants ($M_{age} = 23.37$, Female = 67.92%), covering 131 unique experimental techniques that modulate IMs (frequencies, distress and symptoms; for technique coding schema and preregistered analyses, see Fig. 2; for literature search and screening PRISMA flowchart, see Fig. 3). Table 1 shows summaries of included experiments. Included articles and their detailed coding are given in Supplementary Tables 1 and 11.



Fig. 1 | Descriptives of the coded articles. a, The total number of coded articles by year. b, A word cloud visualizing individual techniques identified in the metaanalysis. Larger sizes and deeper colour represent a greater number of articles investigating the corresponding technique.

Techniques significantly reduced IM frequency (preregistered)

For experiments that had measured IM frequency, techniques significantly reduced overall intrusion frequency (116 techniques, n = 139, k = 370, collected across diary-, lab- and questionnaire-based measures, Hedges' g = 0.16, 95% CI [0.09, 0.23], Z = 4.59, P < 0.001; Fig. 4a). We also found substantial heterogeneity (Q(369) = 922.06, P < 0.001, $I^2 = 64.34\%$, $\tau^2_{\text{experiment}} = 0.13$ at experiment level, and $\tau^2_{\text{outcome}} < 0.001$ at outcome level). Cochran's Q refers to the chi-squared statistic; l^2 is the percentage of total variances in the effect sizes that is due to heterogeneity rather than sampling error; and τ^2 is the tau-squared statistic which provides the variance estimate at the experiment and outcome levels. However, in this omnibus analysis, we did not find credible evidence that techniques would impact intrusion-related distress (Hedges' g = 0.04, 95% CI [-0.03, 0.11], Z = 1.06, P = 0.290) or intrusion-related symptoms (Hedges' g = 0.07, 95% CI [-0.01, 0.16], Z = 1.70, P = 0.089; Fig. 4a), with moderate degree of heterogeneity (Supplementary Table 2). Results remained largely consistent (except for symptoms) after excluding outliers and influential cases (Supplementary Table 2).

Examining publication biases, Egger's test revealed no significant evidence of publication bias (Z = 1.88, P = 0.060). The trim-and-fill procedure imputed 17 artificial effect sizes to adjust for potential publication biases, which resulted in a non-significant effect size, Hedges' g = 0.07, 95% CI [-0.01, 0.14], Z = 1.81, P = 0.070 (Fig. 4b; see Supplementary Fig. 1 and Table 3 for trim-and-fill results of different measures of intrusion frequency, and of distress and symptom outcomes). Complementing these publication biases analyses, we conducted three-parameter selection model analysis (non-preregistered), which showed a significant albeit small effect size in intrusion reduction, Hedges' g = 0.06, 95% CI [0.003, 0.12], Z = 2.06, P = 0.039 (Supplementary Table 4). It is important to note that while the majority of experiments aimed to reduce intrusion frequency and associated distress/symptoms (n = 109), we were surprised to discover how a sizeable number of experiments instead investigated techniques aimed to do the opposite, that is, to increase intrusions and related distress/symptoms (n = 62; Table 1). Combining techniques predicted to decrease and increase intrusions might present a misleading picture of results. Thus, to better understand how different techniques impact intrusions and their associated distress/symptoms, we conducted additional non-preregistered analyses to examine techniques' impact on intrusions based on directional hypotheses for a decrease or increase, as stated in the original article (for hypothesis coding, see Supplementary Table 1).

Techniques aimed to reduce intrusions (non-preregistered). When techniques aimed to reduce intrusions and related outcomes, they significantly reduced overall intrusion frequency (n = 104, k = 194; Hedges' g = 0.31, 95% CI[0.23, 0.39], Z = 7.78, P < 0.001; Fig. 4a). We also found substantial heterogeneity (Q(193) = 482.77, P < 0.001, $f^2 = 62.83\%$, $\tau^2_{experiment} = 0.11$ at experiment level and $\tau^2_{outcome} < 0.001$ at outcome level). In addition, they significantly reduced both intrusion-related distress (n = 44, k = 69; Hedges' g = 0.11, 95% CI[0.03, 0.19], Z = 2.66, P = 0.008) and symptoms (n = 35, k = 47; Hedges' g = 0.22, 95% CI[0.12, 0.32], Z = 4.27, P < 0.001; Fig. 4a), with moderate degree of heterogeneity (Supplementary Table 2). These results remained robust against excluding outliers and influential cases (Supplementary Table 2). For related publication bias analyses (funnel plots and trim-and-fill), see Supplementary Fig. 1 and Table 3.

Techniques aimed to increase intrusions (non-preregistered). When techniques aimed to increase intrusions and related outcomes, they significantly increased overall intrusion frequency (n = 52, k = 105; Hedges'

Coding schema		Example		Preregistered analysis
Verbatim names	Ref. ⁴²	Ref. ¹⁰⁸	Ref. ⁵⁵	
Extract the verbatim names for each experimental and control condition from the articles.	Reactivation + Tetris vs No-task	Reactivation + Tetris vs No-task Abstract Ruminative Thinking vs Distraction Positive Cl Negative Cl	Positive CBM Training vs Negative CBM Training	Pre Peri Immediate Delayed
Step 1: Standardize different names		Film valetad Dumination		post post
Employ uniform naming conventions to consolidate similar or identical techniques in both experimental and control conditions.	Trauma reminder + Tetris vs No-task	vs Control (irrelevant word and reading task)	Positive CBM training vs negative CBM training	Data was split into different timepoints based on the techniques being administered. The following analyses were conducted for each timepoint.
Step 2: Individual technique names				Effectiveness of individual techniques
Code individual technique names for each comparison between experimental vs control condition.	Trauma reminder + Tetris	Film-related rumination	Positive vs Negative CBM Training	 Within each timepoint, three-level multilevel meta- analytical analyses were conducted on every individual technique.
Step 3: Procedure-based superordinate category				Moderation effects of procedure- and
Based on the procedure/approach, each individual technique from Step 2 was further coded as: (a) Pharmacological; (b) Neuromodulation; (c) Behavioural.	Behavioural	Behavioural	Behavioural	mechanism-based category
Given our primary interests, we furthe	er coded behavioural tec	hniques into the following	:	 Within each timepoint, meta-regressions were conducted to examine the moderating effect of Procedure- and
Step 4: Mechanism-based superordinate category				Mechanism-based categories on intrusion frequency and associated outcomes.
 (a) Imagery (b) Verbal (c) Emotion (d) Other (e) Any combinations or contrasts (either through + or vs) 	Imagery	Verbal	Emotion	



g = -0.13, 95% CI [-0.25, -0.02], Z = -2.24, P = 0.025; Fig. 4a). Again, we found substantial heterogeneity ($Q(104) = 250.13, P < 0.001, I^2 = 63.80\%$, $\tau^2_{experiment} = 0.12$ at experiment level and $\tau^2_{outcome} = 0.02$ at outcome level). In addition, they significantly increased intrusion-related distress (n = 26, k = 46; Hedges' g = -0.14, 95% CI [-0.25, -0.03], Z = -2.57, P = 0.010; Fig. 4a) and symptoms (n = 24, k = 30; Hedges' g = -0.19, 95%CI [-0.37, -0.01], Z = -2.04, P = 0.041). Results were largely consistent (except for symptoms) after excluding outliers and influential cases (Supplementary Table 2). For related publication bias analyses (funnel plots and trim-and-fill), see Supplementary Fig. 1 and Table 3.

Timing of technique administration (preregistered)

We coded timepoint of technique administration relative to trauma occurrence, including pre, peri, immediate post (that is, within 24 h post trauma) and delayed post (that is, more than 24 h post trauma). First, using meta-regression, we examined whether Procedure- and Mechanism-based categories as moderators would modulate intrusion frequency, distress and symptoms (Fig. 5, see Supplementary Table 1 for categorizations of each article/technique, see Supplementary Table 5 for mechanism-based techniques). Full results from these timepoint-based moderation analyses are provided in Supplementary Table 6.

Second, employing three-level multilevel meta-analysis, we calculated the effect sizes of individual techniques (Fig. 5). Considering the robustness of results, we report and plot results from individual techniques with a minimum of 3 experiments (for results of all individual techniques, see Supplementary Table 7).

Pre. When administered before analogue trauma exposure, Procedure significantly modulated overall intrusion frequency (Q(2) = 11.43, P = 0.003; Fig. 5). Specifically, administration of Pharmacological techniques significantly increased overall intrusion frequency (n = 6, k = 12; Hedges' g = -0.40, 95% CI[-0.67, -0.13], Z = -2.94, P = 0.003). In contrast, Behavioural and Neuromodulation techniques did not significantly alter overall intrusion frequency (P > 0.128). Within Behavioural techniques, the Mechanism moderator (Imagery, Emotion, Verbal) did not significantly impact overall intrusion frequency (Q(2) = 5.11, P = 0.078). When examining individual techniques, no technique (with $n \ge 3$) significantly altered overall intrusion frequency (P > 0.063; Fig. 5).

Peri. Because only Behavioural techniques were administered during analogue trauma exposure, the Procedure moderation analysis was not conducted. Within Behavioural techniques, the Mechanism moderator significantly modulated overall intrusion frequency (Q(3) = 26.07, P < 0.001). Specifically, Imagery and Emotion techniques significantly reduced overall intrusion frequency with medium effect sizes (Imagery: n = 11, k = 17; Hedges' g = 0.47, 95% CI [0.25, 0.70], Z = 4.18, P < 0.001; Emotion: n = 3, k = 10; Hedges' g = 0.37, 95% CI [0.05, 0.69], Z = 2.24, P = 0.025). When examining individual techniques, concealed Finger Tapping (of a complex pattern) during trauma exposure significantly reduced overall intrusion frequency with a medium effect size (n = 7, k = 12; Hedges' g = 0.57, 95% CI [0.31, 0.84], Z = 4.25, P < 0.001). No other individual techniques (with $n \ge 3$) significantly modulated intrusion frequency.

Immediate Post. When administered immediately after analogue trauma exposure, Procedure did not modulate overall intrusion frequency (Q(1) = 0.01, P = 0.925; Behavioural, n = 77, k = 226; Pharmacological, n = 3, k = 4; there were no Neuromodulation techniques at this timepoint). Within the Behavioural category, the Mechanism moderator (Imagery, Verbal, Emotion, etc.) did not significantly moderate intrusion frequency (Q(5) = 6.43, P = 0.266). When examining individual techniques, the Trauma Reminder + Tetris (vs Trauma Reminder alone) significantly reduced overall intrusion frequency with a large effect size (n = 11, k = 21; Hedges' g = 0.80, 95% CI [0.66, 0.93], Z = 11.59, P < 0.001). Other techniques (with $n \ge 3$) that significantly reduced overall intrusion frequency were: Sleep (n = 8, k = 9;Hedges' g = 0.26, 95% CI [0.10, 0.43], Z = 3.07, P = 0.002); Imagery Re-experience + Eye Movement (n = 3, k = 3; Hedge's g = 0.49, 95% CI [0.13, 0.85], Z = 2.67, P = 0.008) and Imagery Re-experience + Number Counting (*n* = 3, *k* = 3, Hedge's *g* = 0.56, 95% CI [0.12, 1.00], *Z* = 2.51, *P* = 0.012, see Fig. 5).

Delayed Post. When administered at a delayed time (that is, more than 24 h) after analogue trauma exposure, Procedure did not modulate overall intrusion frequency (Q(1) = 0.97, P = 0.325; Behavioural, n = 9, k = 31; Pharmacological, n = 1, k = 2; there were no Neuromodulation techniques at this timepoint). Within the Behavioural techniques, the Mechanism moderator was not significant (Q(1) = 0.39,



Fig. 3 | A PRISMA flowchart of literature search and screening.

P = 0.534). Examining individual techniques with $n \ge 3$, only Trauma Reminder + Tetris (vs No-Task control) technique significantly reduced overall intrusion frequency with a large effect size (n = 3, k = 6; Hedges' g = 0.77, 95% CI [0.07, 1.48], Z = 2.14, P = 0.032).

Impact on intrusion-related outcomes (preregistered). Neither Procedure nor Mechanism significantly modulated intrusion-related distress or symptoms at any of the four timepoints of technique administration (P > 0.09).

Regarding individual techniques (Fig. 6), at Pre trauma, the Positive vs Negative CBM Training showed a large effect size in distress reduction (n = 3, k = 5; Hedges' g = 0.65, 95% CI [0.38, 0.92], P < 0.001). At Immediate Post timepoint, the Trauma Reminder + Tetris (vs Trauma Reminder alone) showed a medium effect size in reducing intrusion-related symptoms (n = 4, k = 4; Hedges' g = 0.37, 95% CI [0.09, 0.64], P = 0.009), and the Imagery Re-experience + Number Counting technique showed a medium-to-large effect size in intrusion-related symptoms reduction (n = 3, k = 3; Hedges' g = 0.56, 95% CI [0.23, 0.89], P < 0.001).

Mode of intrusion measurement (preregistered). The mode of measurement of IMs (for example diary-, lab-, or questionnaire-based) did not significantly modulate overall intrusion frequency (P = 0.316; see Supplementary Table 8).

In addition to the above preregistered analyses within each timepoint of technique administration, we conducted preregistered moderation analyses, including (1) across the whole dataset, whether demographic and experiment-related factors would moderate the overall intrusion frequency and associated outcomes (Supplementary Table 8); (2) within Procedure- and Mechanism-based categories, whether different timepoints may moderate the effectiveness (Supplementary Tables 9 and 10). Internal bias assessments are provided in Supplementary Table 11.

Discussion

In this preregistered systematic review and meta-analysis, we synthesized 606 effect sizes from the 131 techniques that aimed to modulate intrusive memories (IMs, intrusion frequency, distress and symptoms) arising from lab-analogue trauma exposure. Overall, all techniques

(Immediate: g = 0.80, 95% CI [0.66, 0.93]; Delay: g = 0.77, 95% CI [0.07, 1.48]) as well as in alleviating intrusion-related symptoms when admin-

istered immediately post trauma. In particular, benefits observed when techniques administered after a delay are consistent with hypotheses derived from a memory reconsolidation account, which posits that even older memories can be updated when reactivated^{33,41}. In the context of trauma, a brief trauma reminder may reactivate part of the trauma memory traces (for example, a hotspot), rendering it labile and susceptible to interference^{32,42,43}. Playing a game such as Tetris that occupies visuospatial perceptual processing is then hypothesized to

Table 1 | Summary statistics for the studies included in the meta-analysis

Summary statistics	
n (Total experiments)	153
k (Total effect sizes)	606
N (Total sample sizes)	12,074
Demographic information	
Age, mean (s.d.)	23.37 (3.47)
Gender	
Male, N (%)	3,873 (32.08%)
Female, N (%)	8,201 (67.92%)
Countries/Regions	
England, n (%)	50 (32.68%)
the Netherlands, <i>n</i> (%)	29 (18.95%)
Australia, n (%)	24 (15.69%)
Germany, n (%)	19 (12.42%)
USA, n (%)	14 (9.15%)
Others, n (%)	17 (11.11%)
Experimental design	
Between-participant, n (%)	145 (94.77%)
Within-participant, n (%)	8 (5.23%)
Experimental hypothesis directions ^a	
Intrusion increase, n	62
Intrusion decrease, n	109
Unspecified, n	38
Null, n	2
Intrusion outcomes	
Intrusion frequency, n	139
Intrusion-related distress, n	66
Intrusion-related symptoms, n	56

^aNote that the total number of experiments (*n*=153) did not align with the sum of experiments stemming from various hypothesis directions (*n*=211). This disparity arose because some experiments entailed more than two conditions and tested multiple hypothesis directions.

combined significantly reduced intrusions (g = 0.16, 95% CI [0.09, 0.23]), possibly owing to the fact that the majority of the experiments (n = 109) aimed to reduce intrusions. Notably, when we explored these techniques hypothesized in the original papers to reduce IMs, they not only reduced intrusion frequency (g = 0.31, 95% CI [0.23, 0.39]) but also alleviated intrusion-related distress (g = 0.11, 95% CI [0.03, 0.19]) and symptoms (g = 0.22, 95% CI [0.12, 0.32]). Conversely, techniques that aimed to increase IMs indeed increased intrusion frequency (g = -0.14, 95% CI [-0.25, -0.02]) as well as distress (g = -0.14, 95% CI [-0.25, -0.03]) and symptoms (g = -0.19, 95% CI [-0.37, -0.01]). Thus, modulating IMs has generalized impact on intrusion frequency, intrusion-related distress and symptoms. These results highlight IM's centrality in PTSD-like symptoms¹¹⁻¹³ and suggest that targeting IMs in an intervention may benefit other aspects related to psychopathology¹⁵.

Our meta-analysis provides various insights regarding when and which techniques are effective in modulating IMs. Notably, certain post-trauma techniques (that is, those administered after lab-analogue trauma exposure) that tap into mental imagery processes were among the most effective techniques, showing large effect sizes in intrusion frequency reduction even when administered after a delay. More specifically, at both post-trauma timepoints (immediate and delay), playing Tetris following a trauma reminder was effective in reducing intrusions

interfere with the visuoperceptual nature of IMs, rendering them less likely to be triggered and re-occur⁴⁴⁻⁴⁶.
 When administered during analogue trauma exposure, an imagery technique: concealed Finger Tapping of complex patterns was found to also significantly reduce intrusion frequency. Complex spatial Finger Tapping is thought to compete for limited visuospatial working memory resources during mental imagery processing, thereby reducing imagery vividness⁴⁴. Therefore, it is hypothesized to disrupt the encoding of visuoperceptual details of trauma content, leading to reduced IMs^{47,48}. Together, these findings are consistent with the

dual-representation account (DRA)^{30,49} and the Cognitive model of PTSD⁹ that emphasize heightened visuoperceptual processing of trauma memory to lead to intrusive memories, and specifically disrupting visuoperceptual processing during encoding would reduce the likelihood of occurrence of sensory-driven intrusions.

The DRA also proposes that contextualizing trauma memories should reduce IMs. Contextualization is thought to help integrate trauma memories into one's autobiographical memory, allowing such memories to be more susceptible to inhibitory control processes mediated by the prefrontal cortex, ultimately decreasing the frequency of IMs³⁰. However, in our meta-analysis, the experimental technique Contextual Information processing, which provides additional contextual information about trauma material, did not significantly modulate intrusion frequency when administered during trauma exposure (Fig. 5)⁵⁰. In fact, when administered before trauma exposure, this technique increased IMs, although this analysis included only two effect sizes (see Supplementary Table 7). There may be differences between this technique and that intended by DRA; nevertheless, this raises questions for trauma treatment about whether and in which circumstances to consider using contextual information processing or another form of the technique^{50,51}.

Although recent work shows promising results for Imagery Rescripting²³, our findings suggest that administering an analogue version of Imagery Rescripting immediately post trauma did not yield credible evidence favouring intrusion reduction, despite the highly comparable effect sizes to a previous meta-analysis²³ (Hedges' g = 0.29, 95% CI [-0.08, 0.65] in our meta-analysis vs Hedges' g = 0.31, 95% CI [-0.08, 0.65] in our meta-analysis²³). This discrepancy could be due to different analytical approaches: while the previous meta-analysis²³ combined both immediate and delayed post-trauma Imagery Rescripting, our meta-analysis distinguished between these two timepoints of administration and thus included fewer datasets for each timepoint. Nevertheless, given the highly comparable effect sizes in intrusion reduction, future research should further examine the effectiveness of Imagery Rescripting in lab and clinical settings.

PTSD and IMs models propose that changing emotional processing, particularly the negative (re)appraisal or distress associated with trauma, may also reduce IMs^{9,19}. Our meta-analysis examined Emotion techniques, including Positive vs Negative CBM Training and Emotional Reappraisal/Acceptance/Suppression^{22,52-54}. For example, Positive CBM Training aims to shift individuals away from negative reappraisal styles regarding experiencing IMs²¹. Our findings indicated that when implemented before trauma exposure, Positive CBM Training reduced subsequent intrusion-related distress^{54,55}, and it did not impact on IM frequency. When administered after the trauma, Positive CBM Training did not yield any significant results (Fig. 6)^{21,56}. Interestingly, one clinical

Aggregate effect sizes for different outcomes and hypothesis directions а

Outcome	Ν	n	k	All direction	Hedges' g [95% CI]	Р
Overall intrusion frequency	10,765	139	370		0.16 [0.09, 0.23]	<0.001
Diary-based intrusion frequency	8,985	121	248	⊢-∎1	0.14 [0.07, 0.21]	<0.001
Lab-based intrusion frequency	2,859	39	79	↓ ⊢	0.3 [0.17, 0.43]	<0.001
Questionnaire-based intrusion frequency	1,715	17	43		0.13 [-0.04, 0.31]	0.137
Intrusion-related distress	5,690	66	136	↓ ↓ ↓ ■	0.04 [-0.03, 0.11]	0.290
Intrusion symptoms	4,730	55	100		0.07 [-0.01, 0.16]	0.089
N: number of participants				-0.2 0 0.2 0.4		
n: number of experiments						
k: number of effect sizes				Increase Decrease		
Outcome	Ν	n	k	Decrease	Hedges' g [95% CI]	Р
Overall intrusion frequency	8,069	104	194	⊢∎	0.31 [0.23, 0.39]	<0.001
Diary-based intrusion frequency	6,619	89	134		0.29 [0.21, 0.37]	<0.001
Lab-based intrusion frequency	2,052	28	34	·	0.47 [0.32, 0.62]	<0.001
Questionnaire-based intrusion frequency	1,291	13	26	·•	0.27 [0.06, 0.49]	0.012
Intrusion-related distress	3,881	44	69	⊢ → ■ →→	0.11 [0.03, 0.19]	0.008
Intrusion symptoms	3,026	35	47	⊢	0.22 [0.12, 0.32]	<0.001
N: number of participants				-0.2 0 0.2 0.4		
n: number of experiments				← − − − − −	>	
k: number of effect sizes				Increase Decrease		
Outcome	Ν	n	k	Increase	Hedges' g [95% CI]	Р
Overall intrusion frequency	4,097	52	105	⊢	-0.13 [-0.25, -0.02]	0.025
Diary-based intrusion frequency	3,611	47	63	⊨	-0.17 [-0.30, -0.03]	0.015
Lab-based intrusion frequency	1,357	16	32	⊢	0.05 [-0.16, 0.26]	0.620
Questionnaire-based intrusion frequency	487	6	10		-0.04 [-0.20, 0.13]	0.671
Intrusion-related distress	2,190	26	46	⊢	-0.14 [-0.25, -0.03]	0.010
Intrusion symptoms	2,198	24	30		-0.19 [-0.37, -0.01]	0.041
N: number of participants n: number of experiments k: number of effect sizes				-0.3 0 0	3	





Fig. 4 | Results of the main analysis. a, Overall effect sizes for all techniques and for techniques that were hypothesized to decrease/increase the intrusions. Hedge's g and P values were extracted from the three-level multilevel meta-analytical modelling (two-sided z-tests). Forest plots represent the mean

effect sizes, with error bars representing 95% confidence intervals. ${\bf b}$, The contour-enhanced funnel plots examining publication biases. Imputed studies were calculated using the trim-and-fill method.

Imputed studies

2

Outcome: Overall intrusion frequency

Analysis Moderation Analysis: Procedure-based Category Behavioural Pharmacological	N 753 489 118 y	n 13 6 1	k 25 12		 	Hedges' g [95% CI] Q _M = 11.43	P 0.003	N	n	k			Hedges' g [95% CI]	Р
Moderation Analysis: Procedure-based Category Behavioural Pharmacological	753 489 118 y	13 6 1	25 12	, - ,		Q _M = 11.43	0.003							
Behavioural Pharmacological	753 489 118 y	13 6 1	25 12	·•	- i -∎i							1		
Pharmacological	489 118 y	6 1	12			0.14 [-0.04, 0.33]	0.128	NA	NA	NA			NA	NA
i narnacotogicat	118 y	1	~		1	-0.4 [-0.67, -0.13]	0.003	NA	NA	NA			NA	NA
Neuromodulation	у		2		⊹ • →	0.23 [-0.38, 0.83]	0.464	NA	NA	NA		1	NA	NA
Moderation Analysis: Mechanism-based Categor					1	Q _M = 5.11	0.078						Q _M = 26.07	<0.001
Imagery	120	2	3	⊢		0.31 [-0.19, 0.80]	0.223	750	11	17			0.47 [0.25, 0.70]	<0.001
Verbal	80	2	2		÷	-0.4 [-0.90, 0.10]	0.114	933	13	24		4	-0.16 [-0.35, 0.03]	0.093
Emotion	291	5	9	F		0.22 [-0.10, 0.54]	0.178	227	3	10			0.37 [0.05, 0.69]	0.025
Verbal vs Imagery	NA	NA	NA		ł	NA	NA	NA	NA	NA			NA	NA
Imagery vs Verbal	NA	NA	NA		1	NA	NA	50	1	1		→	0.58 [-0.24, 1.39]	0.166
Verbal + Imagery	NA	NA	NA		1	NA	NA	NA	NA	NA			NA	NA
Imagery + Verbal	NA	NA	NA		1	NA	NA	NA	NA	NA			NA	NA
Individual Techniques														
Trauma Reminder + Tetris vs Trauma Reminder	NA	NA	NA		i i	NA	NA	NA	NA	NA		1	NA	NA
Trauma Reminder + Tetris	NA	NA	NA		1	NA	NA	NA	NA	NA		1	NA	NA
Sleep	NA	NA	NA		1	NA	NA	NA	NA	NA			NA	NA
Imagery Re-experience + Eye Movement	NA	NA	NA		i i	NA	NA	NA	NA	NA			NA	NA
Imagery Re-experience + Number Counting	NA	NA	NA			NA	NA	NA	NA	NA			NA	NA
Imagery Re-experience	NA	NA	NA		ł	NA	NA	NA	NA	NA			NA	NA
Film-related Rumination	NA	NA	NA			NA	NA	NA	NA	NA		1	NA	NA
Positive vs Negative CBM Training	147	3	6		+	0.27 [-0.23, 0.77]	0.284	NA	NA	NA		1	NA	NA
Imagery Rescripting	NA	NA	NA		i i	NA	NA	NA	NA	NA			NA	NA
Autobiographical Memory Elaboration	NA	NA	NA			NA	NA	NA	NA	NA			NA	NA
Finger Tapping	NA	NA	NA			NA	NA	360	7	12			0.57 [0.31, 0.84]	<0.001
Number Counting	NA	NA	NA			NA	NA	396	7	11			-0.17 [-0.62, 0.29]	0.471
Contextual Information	NA	NA	NA		1	NA	NA	244	4	8		÷	-0.2 [-0.47, 0.07]	0.142
Dissociation	NA	NA	NA		i i	NA	NA	128	3	4			-0.01 [-0.61, 0.59]	0.973
High-dose Alcohol	194	3	3		÷	-0.22 [-0.74, 0.30]	0.404	NA	NA	NA			NA	NA
Low-dose Alcohol	194	3	3		+	-0.49 [-1.01, 0.03]	0.063	NA	NA	NA		ł	NA	NA
N: Number of Participants n: Number of Experiments k: Number of Effect Sizes			-1	.0 -0.5 ease intrusion	0 0.5 Decrease i	ntrusion			.⊲ Ir	<	-0.5 e intrusion	0 0.5		

Timepoint of technique administration				Immediate p	ost		Delayed post					
Analysis	N	n	k		Hedges' g [95% CI]	Р	N	n	k		Hedges' g [95% CI]	Р
Moderation Analysis: Procedure-based Category					Q _M = 0.01	0.925				1	Q _M = 0.97	0.325
Behavioural	6,042	2 77	226	i 🛏	0.23 [0.15, 0.31]	<0.001	1,018	9	31	÷	0.26 [-0.02, 0.54]	0.069
Pharmacological	340	3	4		0.21 [-0.23, 0.65]	0.35	65	1	2 ←		-0.19 [-1.05, 0.67]	0.66
Neuromodulation	NA	NA	NA	ł	NA	NA	NA	NA	NA	1	NA	NA
Moderation Analysis: Mechanism-based Category					Q _M = 6.43	0.266					Q _M = 0.39	0.534
Imagery	2,933	37	96	+ -	0.31 [0.18, 0.43]	<0.001	837	8	27	u <mark>¦∎</mark> i	0.27 [-0.05, 0.59]	0.104
Verbal	1,135	15	53	i	0.16 [-0.02, 0.34]	0.076	140	2	2 ⊢		▶ 0.44 [-0.14, 1.02]	0.136
Emotion	1,023	10	16		0.01 [-0.24, 0.26]	0.928	NA	NA	NA		NA	NA
Verbal vs Imagery	107	2	2		0.36 [-0.27, 1.00]	0.264	NA	NA	NA	1	NA	NA
Imagery vs Verbal	NA	NA	NA		NA	NA	NA	NA	NA		NA	NA
Verbal + Imagery	200	2	6	<u>├</u>	0.35 [0.02, 0.67]	0.038	NA	NA	NA	1	NA	NA
Imagery + Verbal	575	7	9	·+	0.18 [-0.09, 0.45]	0.199	NA	NA	NA	i i	NA	NA
Individual Techniques												
Trauma Reminder + Tetris vs Trauma Reminder	607	11	21		0.8 [0.66, 0.93]	<0.001	NA	NA	NA		NA	NA
Trauma Reminder + Tetris	NA	NA	NA		NA	NA	273	3	6		· 0.77 [0.07, 1.48]	0.032
Sleep	552	8	9	¦ ⊷•→	0.26 [0.10, 0.43]	0.002	NA	NA	NA	1	NA	NA
Imagery Re-experience + Eye Movement	250	3	3		0.49 [0.13, 0.85]	0.008	NA	NA	NA	i i	NA	NA
Imagery Re-experience + Number Counting	250	3	3	·	0.56 [0.12, 1.00]	0.012	NA	NA	NA	1	NA	NA
Imagery Re-experience	880	8	9	⊢	0.11 [-0.09, 0.32]	0.285	NA	NA	NA		NA	NA
Film-related Rumination	370	5	16		-0.23 [-0.78, 0.33]	0.42	NA	NA	NA		NA	NA
Positive vs Negative CBM Training	341	3	4	┝┼╼─┥	0.16 [-0.12, 0.44]	0.27	NA	NA	NA	1	NA	NA
Imagery Rescripting	319	3	5	·	0.29 [-0.08, 0.65]	0.123	NA	NA	NA	i i	NA	NA
Autobiographical Memory Elaboration	315	3	6		0.03 [-0.15, 0.21]	0.741	NA	NA	NA	i i	NA	NA
Finger Tapping	NA	NA	NA		NA	NA	NA	NA	NA		NA	NA
Number Counting	NA	NA	NA	ł	NA	NA	NA	NA	NA	1	NA	NA
Contextual Information	NA	NA	NA		NA	NA	NA	NA	NA		NA	NA
Dissociation	NA	NA	NA		NA	NA	NA	NA	NA	1	NA	NA
High-dose Alcohol	NA	NA	NA	i i	NA	NA	NA	NA	NA	i	NA	NA
Low-dose Alcohol	NA	NA	NA		NA	NA	NA	NA	NA		NA	NA
N: Number of Participants				-0.5 0 0.5 1.0					-0.5	0 0.5 1	.0	
k: Number of Effect Sizes			<u> </u>		\rightarrow			+		·	→	

Increase intrusion Decrease intrusion

Increase intrusion Decrease intrusion

Fig. 5 | Results of the moderation analysis and analysis on individual techniques. Effectiveness of Procedure and Mechanism superordinate categories, and individual techniques within each timepoint of technique administration. For individual techniques, the figure shows results with a minimum of 3 experiments within each timepoint ($n \ge 3$). Overall moderation

effects and effect sizes for each level within a moderator were estimated through the meta-regression. Effect sizes for each individual technique were estimated through three-level multilevel modelling. Forest plots represent the mean effect sizes, with error bars representing 95% confidence intervals.

study indicated that Positive CBM Training may alleviate symptoms in PTSD patients⁵⁷. Future research is warranted to investigate the translational value of emotion-modulation techniques.

In addition to techniques hypothesized to tap into single mechanisms or processes, we also coded techniques that tackled multiple mechanisms (for example, imagery and verbal processing, cognitive

	Outco	omes		Overall intrusion frequency	Int dis	rusion-related tress		Intrusion symptoms
	-	-			Pre			
Individual techniques	N	n	k			Hedges' g [95	% CI]	Р
	NA	NA	NA			NA		NA
Trauma Reminder + Tetris vs Trauma Reminder	NA	NA	NA			NA		NA
Tanuna Damiadan (Tataia	NA	NA	NA			NA		NA
Trauma Reminder + Tetris	NA	NA	NA			NA		NA
	NA	NA	NA			NA		NA
Sleep	NA	NA	NA			NA		NA
	NA	NA	NA			NA		NA
Imagany Dalaynarianaa I Eyo Mayamant	NA	NA	NA	1		NA		NA
imagery Re-experience + Eye Movement	NA	NA	NA			NA		NA
	NA	NA	NA			NA		NA
Imagery Re-experience + Number Counting	NA	NA	NA			NA		NA
	NA	NA	NA			NA		NA
Imagery Re-experience	NA	NA	NA	l l		NA		NA
	NA	NA	NA	i		NA		NA
	NA	NA	NA			NA		NA
Film-related Rumination	NA	NA	NA			NA		NA
Desitive of Negative ODM Tasiaia	147	3	6			0.27 [-0.23, 0	.77]	0.284
Positive vs negative CBM Training	147	3	5			0.65 [0.38, 0.	92]	<0.001
N: Number of Participants n: Number of Experiments k: Number of Effect Sizes		÷	oroana	-0.2 0 0.2 0.4	0.6 0.8 1.0			

Increase outcome Decrease outcome

				Immediate post		
Individual techniques	Ν	n	k		Hedges' g [95% CI]	Р
T	607	11	21	+++	0.8 [0.66, 0.93]	<0.001
Trauma Reminder + Tetris vs Trauma Reminder	267	4	4		0.37 [0.09, 0.64]	0.009
Trauma Reminder + Tetris	NA NA	NA NA	NA NA		NA NA	NA NA
Sleep	552 367 295	8 6 5	9 6 5		0.26 [0.10,0.43] 0.12 [-0.10, 0.34] 0 [-0.45, 0.45]	0.002 0.286 0.998
Imagery Re-experience + Eye Movement	250 250	3 3	3 3		0.49 [0.13, 0.85] 0.26 [-0.06, 0.58]	0.008 0.114
Imagery Re-experience + Number Counting	250 250	3 3	3 3		0.56 [0.12, 1.00] 0.56 [0.23, 0.89]	0.012 <0.001
Imagery Re-experience	880 319 236	8 3 3	9 3 4		0.11 [-0.09, 0.32] 0.37 [-0.03, 0.76] -0.14 [-0.63, 0.36]	0.285 0.067 0.593
Film-related Rumination	370 199	5 3	16 12		-0.23 [-0.78, 0.33] -0.14 [-0.30, 0.03]	0.42 0.108
Positive vs Negative CBM Training	341 341	3 3	4 4		0.16 [-0.12, 0.44] -0.09 [-0.30, 0.13]	0.27 0.423
N: Number of Participants				-0.5 0 0.5 1	0	

n: Number of Experiments

k: Number of Effect Sizes

Increase outcome Decrease outcome

				Delayed post		
Individual techniques	Ν	n	k		Hedges' g [95% CI]	Р
Tanuna Damindan (Datais na Tanuna Damindan	NA	NA	NA		NA	NA
Trauma Reminder + Retris vs Trauma Reminder	NA	NA	NA		NA	NA
Trauma Damindar I Tatria	273	3	6	· · · · · · · · · · · · · · · · · · ·	0.77 [0.07, 1.48]	0.032
frauma Reminder + Tetris	273	3	3	► 	0.31 [-0.16, 0.78]	0.19
	NA	NA	NA		NA	NA
Sleep	NA	NA	NA		NA	NA
	NA	NA	NA		NA	NA
Imagony Policyportional + Evo Movement	NA	NA	NA		NA	NA
magery Re-experience + Lye movement	NA	NA	NA		NA	NA
Imagany Re-avpariance Number Counting	NA	NA	NA		NA	NA
Inagery Re-experience + Number Counting	NA	NA	NA		NA	NA
	NA	NA	NA		NA	NA
Imagery Re-experience	NA	NA	NA		NA	NA
	NA	NA	NA		NA	NA
Film related Dumination	NA	NA	NA		NA	NA
Film-related Rumination	NA	NA	NA		NA	NA
Positivo ve Negativo CPM Training	NA	NA	NA		NA	NA
Positive vs Negative CBM fraining	NA	NA	NA		NA	NA
N: Number of Participants				0 0.5 1.0 1.	5	

n: Number of Experiments

k: Number of Effect Sizes

Fig. 6 | Multiple outcomes (intrusion frequency, distress, symptoms) of $individual \, techniques. \, {\sf Individual \, techniques \, with \, more \, than \, 2 \, outcomes}$ and with each outcome having a minimum of 3 experiments ($n \ge 3$) within each timepoint. Three-level multilevel modelling was applied to each individual

Increase outcome Decrease outcome

technique and each outcome within each timepoint. P values were obtained using two-sided z-tests. Forest plots represent the mean effect sizes, with error $bars\,representing\,95\%\,confidence\,intervals.$

and emotional processing). For example, in one article using a dual-task intervention, simultaneous Imagery Re-experience and Number Counting significantly reduced intrusions and intrusion-related symptoms when administered immediately post trauma⁵⁸. These results raise the possibility of combining imagery and verbal processing (for example, number counting and word games⁴³) in reducing IMs. Another technique found to be effective and that taps into multiple mechanisms is post-trauma Sleep²⁴⁻²⁶. Sleep may facilitate the integration of trauma memories into one's autobiographical memory scheme^{59,60}, help restore cognitive control⁶¹⁻⁶³ and alleviate affective response^{64,65}. Such results open interests in new avenues to explore composite interventions that address multiple processing types simultaneously⁶⁶.

One strength of our meta-analysis is that we included Pharmacological and Neuromodulation techniques aimed at modulating IMs. Despite the relatively low number of experiments and the diversity of Pharmacological techniques tested (for example, Alcohol, Nicotine, Oxytocin), results showed that Pharmacological techniques administered pre-trauma significantly increased intrusions. These findings provide valuable insights informing risk factors that may exacerbate traumatic intrusions. Specifically, certain drugs (Nicotine and Oxytocin) may increase intrusions via emotion-relevant mechanisms, such as increasing physiological arousal^{67,68} and heightening sensitivity to emotional cues^{69,70}. Heightened arousal and sensitivity may promote preferential encoding of low-level sensory details of the trauma, resulting in sensory-driven intrusions9. Despite the significant overall effect in increasing intrusions, the low number of experiments per timepoint prevents us from drawing strong conclusions regarding the effectiveness of specific Pharmacological techniques.

Regarding Neuromodulation techniques, research suggests that non-invasive brain stimulation could temporally inhibit or activate neural activity implicated in visual-perceptual processing⁷¹, cognitive control⁷² and emotion regulation⁷³, that are highly relevant for IMs. Specifically, a study employed transcranial direct current stimulation (tDCS) to stimulate the left dorsolateral prefrontal cortex to enhance cognitive control before analogue trauma exposure. Despite the hypothesis that the tDCS would reduce IMs via enhanced cognitive control, results showed that there was no significant effect of tDCS on IMs⁷⁴. Another study found that after viewing a trauma film, disrupting neural activity of the occipital cortex through repetitive transcranial magnetic stimulation (rTMS) reduced emotional intensity of intrusions, although not intrusion frequency⁷⁵. Building on the current meta-analysis, one future avenue is to test whether combining techniques involving both Behavioural/Imagery and Neuromodulation/Pharmacological techniques could improve the effectiveness of specific techniques.

The ecological validity of the lab-analogue trauma exposure paradigm, its limitations and the translational values of our meta-analysis should be discussed. First, lab-analogue trauma exposure (for example, films, images, VR) clearly deviate from real-world trauma exposure in many ways, including self-involvement, emotional intensity, actual threat likelihood and so on. In addition, analogue trauma typically only induces short-lived trauma symptoms that tend to subside within a week, contrasting with the potential severe and long-lasting effects often observed after real-life trauma, and such limitations are further discussed elsewhere¹⁷. We note that our meta-analyses only included experiments conducted in lab settings with non-clinical populations, cautioning against generalization to real-life trauma experiences and clinical populations. However, it is worth noting that repeated or extreme 'indirect' trauma exposure via media (including film), if work related, has been included within the diagnostic criterion for a traumatic event in DSM-5 (ref. 1, p. 271). Studies have shown that indirect exposure to trauma via media can induce acute stress symptoms resembling PTSD-like symptoms^{27,28}. Clearly, we are not equating analogue lab trauma to real trauma, rather that the phenomenon of intrusive memories after witnessing aversive experiences is a continuum.

Recent studies have provided some evidence indicating that intrusion modulation techniques developed in the laboratory may also prove effective in clinical settings. For example, in clinical randomized controlled trials, imagery techniques (for example, Trauma Reminder + Tetris) significantly reduced the number of intrusions arising from real-life trauma such as traumatic childbirth, motor vehicle accidents, or work-related trauma in healthcare staff^{15,76-80}. Consistent with our lab-based meta-analysis showing that similar imagery techniques can reduce intrusions even after a delay, it appears that imagery techniques may at times be effective for traumatic events that occurred weeks or months earlier^{15,80} (see also refs. 39,40,81 for smaller case studies on older traumatic memories). A clinical meta-analysis revealed a medium effect size of g = 0.49,95% CI [0.18, 0.80] in real-world intrusion reduction using the Trauma Reminder + Tetris technique³⁸, smaller than that reported in our meta-analysis (g = 0.77, 95% CI [0.07, 1.48] for Trauma Reminder + Tetris administered at the delayed post-trauma timepoint). The lower effect size is expected, given that clinical studies typically involve heterogeneous participants and trauma types, and are less well controlled than in laboratory settings.

It is important to think carefully about the relationship between studies in the laboratory and clinical settings. The lab studies usually only test post-trauma techniques administered up to 4 days after analogue trauma exposure. The similar pattern of findings with clinical samples, at longer time intervals of intervention administration post-trauma than lab studies, inspires cautious optimism about possibilities to modulate intrusive memories being on a continuum. It may also help alleviate concerns about a different pattern of results emerging (for example, increased IMs) should the time interval be extended. Considering concerns about safety is particularly important given the clinical controversy over critical incident stress debriefing, which in meta-analyses has been shown to worsen symptoms of PTSD after real trauma^{82,83}. Collectively, while in their early days, similarities in the pattern of results that seem to be emerging between lab and clinical studies support the potential of using lab-analogue trauma paradigm¹⁷ for modelling IMs as a treatment development target. In the future, new techniques could be developed for use either as stand-alone interventions, or to complement existing evidence-based interventions or treatments⁸⁴.

Limitations of the current work should be discussed. One limitation is that while our classification of techniques based on their hypothesized mechanisms was informed by existing research and theories. the precise underlying neurobiological mechanisms remain unknown. Understanding the neurobiological mechanisms through which such techniques operate could not only empirically validate their proposed mechanisms but also help identify the conditions under which they are most effective. Another limitation is that we have only focused on IMs in relation to post-traumatic stress conditions such as PTSD, neglecting the relevance of IMs in other disorders (for example, depression, anxiety, bipolar, obsessive-compulsive disorders) and related symptoms such as intrusive thoughts, rumination or excessive worry^{30,85-90} Based on our results, future research should examine whether similar techniques can reduce IMs and intrusion-related symptomatology in these other mental disorders. Third, preregistered experiments are rare (with exceptions^{20,53}), and this may in part be due to the age of some included studies. Based on effect sizes provided by the current and other meta-analyses^{23,26}, future research should conduct preregistered and well-powered studies to improve the evidence base regarding the effectiveness of specific techniques. This is of particular importance, as mentioned above, given the small number of studies in certain subgroups when techniques are divided by timepoint. Lastly, we preregistered that we would perform three-level multilevel meta-analyses for each outcome individually, instead of conducting multivariate analyses⁹¹. Multivariate analyses could be advantageous as it allows researchers to examine various types of outcome (for example, intrusion frequency, distress and symptoms) in a single analysis, accounting

for correlations between outcomes. Future meta-analyses can consider utilizing these advanced multivariate analyses.

To conclude, our meta-analysis provides a comprehensive coverage of the experimental techniques on the modulation of intrusive memories arising from lab-analogue trauma exposure. Via examining 131 unique techniques' effectiveness in modulating intrusions and related symptoms, based on the timepoint of administration, our findings bear both theoretical and translational implications. To facilitate the use of this meta-analysis, we have developed a website so that researchers may interactively analyse this rich dataset to guide future research (https://intrusivememory.shinyapps.io/shinymeta/). Considering that intrusive memories are a transdiagnostic symptom for mental disorders beyond PTSD, such as in depression, anxiety, suicidal thoughts, among others^{30,88}, we hope that our findings can stimulate research in developing innovative interventions targeting at intrusive memory modulation across different psychological disorders.

Methods

We followed the Methodological Expectations of Cochrane Intervention Reviews (MECIR)⁹² in performing our systematic review and meta-analysis, and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines⁹³ in reporting the meta-analysis. This project has been preregistered in the PROSPERO database (07 January 2021; ID: CRD42021224835). All article information, data and calculated effect sizes can be found in Supplementary Table 11. Data and scripts are available in the Open Science Framework⁹⁴. Deviations from preregistered plans are stated below in relevant Methods sections.

Literature search

A literature search was conducted on titles, abstracts and keywords in online databases including Web of Science, PsycINFO (via ProQuest), ProQuest Dissertation, PubMed, BioRxiv, PsyArxiv, Scopus and Embase with keywords referring to intrusive memories and trauma. The exact keywords using Boolean operators are (intrusion* OR "intrusive memor*" OR re-experience* OR "unwanted memor*" OR flashback* OR "involuntary memor*" OR "mental imagery") AND ("emotional memor*" OR "experimental* trauma*" OR "analogue trauma*" OR stress*). Search keywords and fields may vary on the basis of different requirements of the search engines (the exact search words and fields can be found in PROSPERO). As in the preregistration, we initially planned to obtain additional publications through (1) citations from recent review articles (both forward and backward citations), (2) listservers such as Society for Research in Psychopathology and (3) email soliciting unpublished data from all authors published on the captioned topic for meta-analysis. Yet, considering the feasibility and time cost, in actual practice, we obtained additional publications through citations from recent review articles. Unpublished dissertations and preprints were included, with attempts to weigh against publication bias. No date-of-publication criterion was defined. The first literature search was conducted on 15 December 2020, the second update search on 27 April 2022, and the third update search on 12 December 2023. The third search included two additional databases following a reviewer's suggestions: Scopus and Embase.

Inclusion/exclusion criteria

Articles were included on the basis of the following criteria: experimental studies including (1) healthy participants, (2) experimental exposure to analogue forms of trauma (for example, trauma film, emotionally negative images and so on) and (3) experimental technique(s) (including behavioural, pharmacological/substance-related and neuromodulation techniques) targeted at altering the frequency of traumatic intrusive memories. To examine the preregistered outcome intrusion-related symptoms, we additionally included articles and experiments that exclusively examine intrusion-related symptoms. Articles were excluded if they: (1) included clinical populations, (2) were not experimental studies (for example, correlational studies or case studies) or (3) used non-lab, real-world trauma exposure (for example, real-world motor accident).

Article selection and data extraction

Study selection followed PRISMA guidelines: in the screening phase, titles, keywords and abstracts of the studies identified through literature searches (j = 19,661) were screened by two reviewers (M.M.V., S.Z.) to identify potentially relevant studies that meet the aforementioned inclusion/exclusion criteria, resulting in 192 articles.

In the eligibility phase, the full texts of these publications (*j* = 192) were assessed for eligibility by three reviewers independently: M.N.V. and S.Z. assessed all articles, while L.S. assessed a random 7.81% of the articles (*j* = 15). Inter-rater reliability was substantial to almost perfect: 1st search M.M.V. and S.Z.: Cohen's κ = 0.95; 99.27% agreement; 2nd search M.M.V. and S.Z.: Cohen's κ = 1; 100% agreement; 3rd search M.M.V. and S.Z.: Cohen's κ = 1; 100% agreement; M.M.V./S.Z. and L.S.: Cohen's κ = 0.64; 93.75% agreement. Disagreement was reconciled by a fourth team member (X.H.) to reach a consensus. In total, 148 articles^{20-22,42,43,45,47,48,50,52-56,58,59,69,70,74,75,95-221} were eligible and included in the qualitative synthesis and for subsequent data extraction.

Using a standardized Excel form, data for each study were extracted by two independent raters (M.M.V., S.Z.) according to the coding guidebook (see ref. 94). The 148 eligible articles were divided equally between the two raters, with 33.78% of the articles (j = 50) coded by both raters to obtain inter-rater reliability (M.M.V. and S.Z.: Cohen's κ ranged from 0.82 to 1 for primary information). An additional 8.11% of articles from each rater (total j = 12) were coded by L.S. for cross-validation (M.M.V./S.Z. and L.S.: Cohen's $\kappa = 1$). Any discrepancy was discussed among co-authors to reach a consensus. Following the completion of coding, the data were evenly divided and subjected to a thorough review by six research interns. Typos or errors identified by the interns were corrected by M.M.V. and S.Z.

Study coding followed our preregistration: (1) study/sample characteristics (for example, within-/between-participant design; demographics), (2) specific experimental technique and its comparison condition, (2) nature of the experimental trauma exposure (for example, film, images), (4) frequency and measurement of trauma intrusions (descriptive and inferential statistics), (5) descriptive and inferential statistics of additional outcomes (for example, emotional distress), (6) information on risk of bias (that is, based on the internal bias assessment on the quality of the study; see below for the details of internal bias assessment), (7) publication status (published/unpublished) and (8) timepoint of technique administration relative to analogous trauma onset (for example, pre vs peri vs immediate post vs delayed post).

Due to the heterogeneity brought by involving a comprehensive range of techniques, we identified the key experimental techniques and corresponding control conditions based on each study. The control condition could be a no-task condition or an alternative task condition, for example, Trauma reminder + Tetris (experimental condition) vs No-task/Buffer task of music listening (control condition); Sleep (experimental condition) vs Wakefulness (control condition); Oxytocin (experimental condition) vs Placebo (control condition) and so on. If more than 2 experimental conditions were present, experimental and control conditions were identified according to the study. Comparisons were made between each experimental condition and control condition. In the absence of a control condition, we coded the contrast made between the two experimental techniques.

Furthermore, considering that different techniques were hypothesized to either increase or decrease intrusion, we coded the predicted direction of intrusion change for each experiment (non-preregistered). A 'Decrease'/'Increase' direction means that compared with the control condition, the experimental condition was hypothesized to decrease/ increase the intrusion frequency, respectively. In some cases, the authors did not specify the direction or they hypothesized that the two conditions would not differ; here we coded the direction as 'Unspecified' and 'Null', respectively.

We preregistered to report results on the overall intrusion frequency on the basis of one, or more than one of these measures: diary-, lab- or questionnaire-based intrusion frequency. We preregistered to assess intrusion-related emotional distress and intrusion symptoms as measured by the intrusion subscale from the Impact of Event Scale (revised, IES/IES-R^{222,223}) or other similar questionnaires (for example, symptom questionnaire⁹⁹). Due to insufficient data from the included studies/experiments measuring intrusion vividness, we decided to exclude this measure even though we intended to include this outcome in our preregistration.

To assess the quality of each eligible study, an internal bias assessment was conducted, adapting from ref. 224. Disagreement was reconciled through discussion to reach a consensus. Specifically, quality assessment was done by coding each study as to whether it provides information on the following 11 aspects. Each aspect was coded as either 0 for 'not provided', or 1 for 'yes', or 0.5 for partial information reported. Details can be found in the coding guidebook:

- (1) Sample characteristics (age, gender)
- (2) Randomization procedures
- (3) Participants inclusion criteria
- (4) Data exclusion criteria
- (5) Technique/intervention procedures
- (6) Outcome measure and mode of measurement
- (7) Comparable baseline trauma experiences between conditions
- (8) Inter-rater reliability for intrusion scoring (only for studies using intrusion diary)
- (9) Analysis plan
- (10) Whether it is a peer-reviewed publication
- (11) Mood/distress check for experimental trauma induction

The assessment scores for each study can be found in Supplementary Table 11.

Data synthesis and analyses

Effect sizes for each outcome were standardized to Hedges' gusing the standardized mean difference (SMD) method²²⁵, utilizing information provided in the article (for example, raw mean/s.d./s.e., t-score, Cohen's d and so on). The calculation was achieved using custom functions and packages on R, including metafor^{226,227} and esc²²⁸. The SMDs were derived from differences between the experimental conditions and the control/alternative experimental conditions on our outcome measures, including the intrusion frequency, intrusion-related distress and intrusion-related symptoms arising from the lab-analogue trauma exposure. Higher values of Hedges' gs or SMDs with positive signs indicate positive outcomes, such that the experimental condition was associated with fewer intrusions, and lower levels of distress or symptoms than the control/alternative experimental condition. Lower values of Hedges' gs or SMDs with negative signs indicate negative outcomes, such that the experimental condition was associated with more intrusions, and higher levels of distress or symptoms than the control/alternative experimental condition.

To compare the effectiveness of different categories of techniques, we developed a hierarchical coding schema to categorize similar techniques (Fig. 2). Specifically, on the basis of each entry of experimental and control conditions, we developed the following steps, from extracting verbatim names to superordinate categorization (see detail below and in Fig. 2). From Steps 2 to 4, each entry was coded by two raters (M.M.V. and S.Z.) independently: Cohen's κ ranged from 0.57–0.79. Any inconsistency was reconciled by a third rater (X.H.).

(1) Verbatim names of the experimental and control conditions were extracted from the original article.

- (2) Step 1: Standardize names for similar or identical experimental and control conditions across different experiments/articles.
- (3)Step 2: Individual technique names. Code technique names for the experimental vs control condition contrasts. For example. Sleep vs No Sleep comparisons were coded as Sleep: Trauma Reminder + Tetris vs No-Task comparisons were coded as Trauma Reminder + Tetris. Note that in the absence of a control condition, we coded the contrast between two experimental conditions as the technique in this step. For instance, Trauma Reminder + Tetris vs Trauma Reminder comparisons were coded as Trauma Reminder + Tetris vs Trauma Reminder to acknowledge the importance on the inclusion of trauma reminders; Positive CBM Training vs Negative CBM Training was coded as Positive vs Negative CBM Training²¹. Similarly, Imagery Rescripting vs Imagery Re-experience was coded as Imagery Rescripting vs Imagery Re-experience. This approach aids in distinguishing between various types of comparisons during the aggregation of their effect sizes in the corresponding analyses.
- (4) Step 3: Procedure-based superordinate category. We coded each individual technique into one of the following categories:
 (i) Behavioural, (ii) Neuromodulation, (iii) Pharmacological based on their administration procedure. Given that most of the techniques are behavioural, we further coded the behavioural techniques into Mechanism-based superordinate category (see step 4).
- (5) Step 4: Mechanism-based superordinate category. According to the specific mental processes the techniques target, we coded each Behavioural individual technique into one of the following categories: (i) Imagery, that tap into visuospatial or visuoperceptual processing (for example, imagery rescripting/ re-experience, data-driven processing, finger tapping and so on); (ii) Verbal, that tap into verbal processing (for example, rumination, conceptual processing, number counting and so on); (iii) Emotion (for example, emotional suppression, guilt induction, stress induction, positive cognitive bias modification and so on); (iv) Others, when techniques may tap into unspecified or multiple mechanisms (for example, sleep, self-efficacy, exercises and so on); (v) any combinations or contrasts (for example, Imagery + Verbal, Imagery vs Verbal). Note that in our Mechanism-based moderation analysis, we excluded the category of 'Others' and any combinations with 'Others'. considering the heterogeneity of techniques in this category.

We additionally coded two superordinate categories on the basis of the task characteristics of each Behavioural individual technique: (1) Direct vs Indirect involvement of trauma content: on the basis of whether the techniques directly vs indirectly target the trauma memory, we coded those involving direct engagement of trauma content as Direct and others that do not require direct confrontation as Indirect; and (2) Task vs Instruction: on the basis of each technique's modality, we classified techniques into Task category if a technique required participants to perform a concrete task entailing external action (for example, finger tapping, viewing a humour inducing film, listening to a meditation recording, ingesting a pharmaceutical drug). For techniques that required participants to adopt a specific style of thinking and did not involve any external action, we coded them into Instruction category (for example, elaboration, abstract processing, mentally rehearsing, thought suppression). In cases where the experimental and comparison groups employed different modalities of techniques, we coded the comparison with 'vs' in the middle (for example, Task vs Instruction). Results related to these two superordinate categories are reported in Supplementary Table 8.

Following our preregistration, we coded the timepoint of technique administration, and examined the effectiveness of individual techniques and the moderation effect of superordinate categories of techniques within each timepoint. Specifically, we coded the timepoint as Pre, Peri, Immediate Post, or Delayed Post relative to the onset of analogue trauma exposure. Techniques that were administered within the same day after the experimental trauma were categorized as Immediate Post, and techniques administered at least 24 h after the trauma exposure were categorized under Delayed Post. Techniques that were used in multiple timepoints were coded with '+', for example, Peri + Immediate Post.

Main analyses

We used 'rma.mv' from the metafor package²²⁷ to calculate overall effect sizes (that is, main analyses). In addition to calculating effect sizes using the whole dataset, we further divided the data into different hypothesized directions considering each experiment/technique's hypothesis in modulating intrusion frequency (Decrease, Increase and Unspecified). These analyses were conducted on both overall intrusion frequency (aggregating across diary-, lab- and questionnaire-based intrusion frequency) and on individual measurement. A three-level multilevel meta-analytical approach^{229,230} was used to model three levels of variance: (1) variances due to sampling error, (2) within-study variances among multiple effect sizes from the same experiment and (3) variances due to between-study heterogeneity. To measure heterogeneity, we reported Cochran's Qas results of chi-squared analyses and I^2 as the percentage of total variances across effect sizes that is due to heterogeneity rather than sampling error or chance; τ^2 provides the variance estimate at the experiment and outcome levels. We next repeated the analyses on other preregistered outcomes: intrusion-related distress and intrusion-related symptoms.

Publication bias analyses

We conducted publication bias analyses on each of the outcomes using: (1) contour-enhanced funnel plots, which were used to display the presence of publication bias²³¹, (2) Egger's test, which was used to quantify the funnel plot assessment findings²³², calculated by using the standard errors of the effect sizes as a predictor in the meta-regression. (3) Trim-and-fill method, to impute artificial effect sizes that are missing due to the impact of publication bias on literature search findings, and then calculate corrected effect sizes²³³, and (4) non-preregistered three-parameter selection model analysis²³⁴.

Moderation analyses

We used 'rma.mv' from the metafor package²²⁷ to conduct moderation analyses on intrusion frequency, intrusion-related distress and intrusion-related symptoms. Following our preregistration, to examine the effectiveness of different superordinate categories within each timepoint of technique administration, we split data into different timepoints of technique administration (Pre, Peri, Immediate Post, Delayed Post, and so on), then we conducted meta-regressions within each timepoint using the following two moderators: Procedure- and Mechanism-based superordinate category.

We next examined whether the timepoint of technique administration may moderate the effectiveness within specific superordinate categories (that is, Procedure- and Mechanism-based). Similarly, we split data into different superordinate categories and conducted meta-regressions.

Furthermore, across the entire dataset, we conducted metaregressions using the following moderators (reported in Supplementary Table 8):

- (1) Procedure-based superordinate category
- (2) Mechanism-based superordinate category
- (3) Direct/Indirect involvement of trauma content
- (4) Task- vs Instruction-based techniques
- (5) Time of techniques being administered (for example, Pre, Peri, Post and so on, non-preregistered)

- (6) Nature of experimental trauma exposure (for example, film, images, and so on)
- (7) Nature of comparison condition (passive (no-task) or active (alternative task) control)
- (8) Study design (within- vs between-participant)
- (9) Mode of intrusion measurement (for example, intrusion diary and so on)
- (10) Neuroimaging or psychophysiological measures included (yes vs no)
- (11) Publication status (published vs unpublished)
- (12) Gender
- (13) Age
- (14) Country/Region
- (15) Continent

Analyses of individual techniques

In addition, we preregistered to examine the effectiveness of individual techniques (coded in Step 2, Fig. 2) within each timepoint of technique administration (for example, Pre, Peri, Immediate Post, Delay Post). We conducted three-level multilevel modelling to calculate the effect sizes of each individual technique within different timepoints of administration.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Data are available on OSF at https://osf.io/phu7w/ (ref. 94). A website was developed for researchers to use the dataset to implement analyses (https://intrusivememory.shinyapps.io/shinymeta/).

Code availability

Codes are available on OSF at https://osf.io/phu7w/ (ref. 94).

References

- 1. Diagnostic and Statistical Manual of Mental Disorders (DSM-5-TR) (American Psychiatric Association, 2013).
- 2. How Common is PTSD in Adults? (US Department of Veterans Affairs, 2018).
- Ehlers, A., Hackmann, A. & Michael, T. Intrusive re-experiencing in post-traumatic stress disorder: phenomenology, theory, and therapy. *Memory* 12, 403–415 (2004).
- 4. Hoppe, J. M. et al. Hotspots in the immediate aftermath of trauma mental imagery of worst moments highlighting time, space and motion. *Conscious. Cogn.* **99**, 103286 (2022).
- Iyadurai, L. et al. Intrusive memories of trauma: a target for research bridging cognitive science and its clinical application. *Clin. Psychol. Rev.* 69, 67–82 (2019).
- Singh, L., Espinosa, L., Ji, J. L., Moulds, M. L. & Holmes, E. A. Developing thinking around mental health science: the example of intrusive, emotional mental imagery after psychological trauma. *Cogn. Neuropsychiatry* 25, 348–363 (2020).
- 7. Brewin, C. R. Episodic memory, perceptual memory, and their interaction: foundations for a theory of posttraumatic stress disorder. *Psychol. Bull.* **140**, 69–97 (2014).
- Brewin, C. R. & Holmes, E. A. Psychological theories of posttraumatic stress disorder. *Clin. Psychol. Rev.* 23, 339–376 (2003).
- 9. Ehlers, A. & Clark, D. M. A cognitive model of posttraumatic stress disorder. *Behav. Res. Ther.* **38**, 319–345 (2000).
- Davis, L. L. et al. The economic burden of posttraumatic stress disorder in the United States from a societal perspective. J. Clin. Psychiatry 83, 40672 (2022).

- Bryant, R. A. et al. Acute and chronic posttraumatic stress symptoms in the emergence of posttraumatic stress disorder: a network analysis. JAMA Psychiatry 74, 135–142 (2017).
- Fried, E. I. et al. Replicability and generalizability of posttraumatic stress disorder (PTSD) networks: a cross-cultural multisite study of PTSD symptoms in four trauma patient samples. *Clin. Psychol. Sci.* 6, 335–351 (2018).
- McNally, R. J. et al. Mental disorders as causal systems: a network approach to posttraumatic stress disorder. *Clin. Psychol. Sci.* 3, 836–849 (2015).
- 14. Bringmann, L. F. et al. What do centrality measures measure in psychological networks? J. Abnorm. Psychol. **128**, 892–903 (2019).
- Iyadurai, L. et al. Reducing intrusive memories after trauma via an imagery-competing task intervention in COVID-19 intensive care staff: a randomised controlled trial. *Transl. Psychiatry* 13, 290 (2023).
- Holmes, E. A. & Bourne, C. Inducing and modulating intrusive emotional memories: a review of the trauma film paradigm. *Acta Psychol.* **127**, 553–566 (2008).
- 17. James, E. L. et al. The trauma film paradigm as an experimental psychopathology model of psychological trauma: intrusive memories and beyond. *Clin. Psychol. Rev.* **47**, 106–142 (2016).
- Lau-Zhu, A., Holmes, E. A. & Porcheret, K. Intrusive memories of trauma in the laboratory: methodological developments and future directions. *Curr. Behav. Neurosci. Rep.* 5, 61–71 (2018).
- Marks, E. H., Franklin, A. R. & Zoellner, L. A. Can't get it out of my mind: a systematic review of predictors of intrusive memories of distressing events. *Psychol. Bull.* 144, 584–640 (2018).
- Varma, M. M. & Hu, X. Prosocial behaviour reduces unwanted intrusions of experimental traumatic memories. *Behav. Res. Ther.* 148, 103998 (2022).
- Woud, M. L., Holmes, E. A., Postma, P., Dalgleish, T. & Mackintosh, B. Ameliorating intrusive memories of distressing experiences using computerized reappraisal training. *Emotion* 12, 778–784 (2012).
- 22. Woud, M. L. et al. Does napping enhance the effects of Cognitive Bias Modification-Appraisal training? An experimental study. *PLoS ONE* **13**, e0192837 (2018).
- 23. Asselbergs, J. et al. A systematic review and meta-analysis of the effect of cognitive interventions to prevent intrusive memories using the trauma film paradigm. *J. Psychiatr. Res.* **159**, 116–129 (2023).
- 24. Davidson, P. & Marcusson-Clavertz, D. The effect of sleep on intrusive memories in daily life: a systematic review and metaanalysis of trauma film experiments. *Sleep* **46**, zsac280 (2023).
- Larson, O., Schapiro, A. C. & Gehrman, P. R. Effect of sleep manipulations on intrusive memories after exposure to an experimental analogue trauma: a meta-analytic review. Sleep Med. Rev. 69, 101768 (2023).
- Schäfer, S. K. et al. To sleep or not to sleep, that is the question: a systematic review and meta-analysis on the effect of post-trauma sleep on intrusive memories of analog trauma. *Behav. Res. Ther.* 167, 104359 (2023).
- Holman, E. A., Garfin, D. R. & Silver, R. C. Media's role in broadcasting acute stress following the Boston Marathon bombings. *Proc. Natl Acad. Sci. USA* 111, 93–98 (2014).
- 28. Silver, R. C. et al. Mental- and physical-health effects of acute exposure to media images of the September 11, 2001, attacks and the Iraq War. *Psychol. Sci.* **24**, 1623–1634 (2013).
- Singh, L., Ahmed Pihlgren, S., Holmes, E. A. & Moulds, M. L. Using a daily diary for monitoring intrusive memories of trauma: a translational data synthesis study exploring convergent validity. *Int. J. Methods Psychiatr. Res.* 32, e1936 (2023).
- Brewin, C. R., Gregory, J. D., Lipton, M. & Burgess, N. Intrusive images in psychological disorders: characteristics, neural mechanisms, and treatment implications. *Psychol. Rev.* **117**, 210–232 (2010).

- Brewin, C. R., Dalgleish, T. & Joseph, S. A dual representation theory of posttraumatic stress disorder. *Psychol. Rev.* **103**, 670–686 (1996).
- 32. Visser, R. M., Lau-Zhu, A., Henson, R. N. & Holmes, E. A. Multiple memory systems, multiple time points: how science can inform treatment to control the expression of unwanted emotional memories. *Phil. Trans. R. Soc. B* **373**, 20170209 (2018).
- 33. Dudai, Y. The restless engram: consolidations never end. Annu. Rev. Neurosci. **35**, 227–247 (2012).
- 34. Nader, K. & Hardt, O. A single standard for memory: the case for reconsolidation. *Nat. Rev. Neurosci.* **10**, 224–234 (2009).
- 35. Phelps, E. A. & Hofmann, S. G. Memory editing from science fiction to clinical practice. *Nature* **572**, 43–50 (2019).
- Schafe, G. E., Nader, K., Blair, H. T. & LeDoux, J. E. Memory consolidation of Pavlovian fear conditioning: a cellular and molecular perspective. *Trends Neurosci.* 24, 540–546 (2001).
- Scully, I. D., Napper, L. E. & Hupbach, A. Does reactivation trigger episodic memory change? A meta-analysis. *Neurobiol. Learn. Mem.* 142, 99–107 (2017).
- Astill Wright, L., Horstmann, L., Holmes, E. A. & Bisson, J. I. Consolidation/reconsolidation therapies for the prevention and treatment of PTSD and re-experiencing: a systematic review and meta-analysis. *Transl. Psychiatry* 11, 453 (2021).
- Kessler, H. et al. Reducing intrusive memories of trauma using a visuospatial interference intervention with inpatients with posttraumatic stress disorder (PTSD). J. Consult. Clin. Psychol. 86, 1076–1090 (2018).
- 40. Thorarinsdottir, K. et al. Reducing intrusive memories of childhood trauma using a visuospatial intervention: case study in Iceland. *JMIR Form. Res.* **5**, e29873 (2021).
- 41. Lee, J. L., Nader, K. & Schiller, D. An update on memory reconsolidation updating. *Trends Cogn. Sci.* **21**, 531–545 (2017).
- 42. James, E. L. et al. Computer game play reduces intrusive memories of experimental trauma via reconsolidation-update mechanisms. *Psychol. Sci.* **26**, 1201–1215 (2015).
- Hagenaars, M. A., Holmes, E. A., Klaassen, F. & Elzinga, B. Tetris and word games lead to fewer intrusive memories when applied several days after analogue trauma. *Eur. J. Psychotraumatol.* 8, 1386959 (2017).
- 44. Baddeley, A. D. & Andrade, J. Working memory and the vividness of imagery. J. Exp. Psychol. Gen. **129**, 126–145 (2000).
- Holmes, E. A., James, E. L., Coode-Bate, T. & Deeprose, C. Can playing the computer game "Tetris" reduce the build-up of flashbacks for trauma? A proposal from cognitive science. *PLoS ONE* 4, e4153 (2009).
- Agren, T., Hoppe, J. M., Singh, L., Holmes, E. A. & Rosén, J. The neural basis of Tetris gameplay: implicating the role of visuospatial processing. *Curr. Psychol.* 42, 8156–8163 (2023).
- 47. Bourne, C., Frasquilho, F., Roth, A. D. & Holmes, E. A. Is it mere distraction? Peri-traumatic verbal tasks can increase analogue flashbacks but reduce voluntary memory performance. *J. Behav. Ther. Exp. Psychiatry* **41**, 316–324 (2010).
- Holmes, E. A., Brewin, C. R. & Hennessy, R. G. Trauma films, information processing, and intrusive memory development. *J. Exp. Psychol. Gen.* 133, 3–22 (2004).
- Brewin, C. R. A cognitive neuroscience account of posttraumatic stress disorder and its treatment. *Behav. Res. Ther.* **39**, 373–393 (2001).
- Pearson, D. G., Ross, F. D. & Webster, V. L. The importance of context: evidence that contextual representations increase intrusive memories. *J. Behav. Ther. Exp. Psychiatry* 43, 573–580 (2012).
- 51. Brewin, C. R. & Burgess, N. Contextualisation in the revised dual representation theory of PTSD: a response to Pearson and colleagues. *J. Behav. Ther. Exp. Psychiatry* **45**, 217–219 (2014).

Article

- Article
- Dunn, B. D., Billotti, D., Murphy, V. & Dalgleish, T. The consequences of effortful emotion regulation when processing distressing material: a comparison of suppression and acceptance. *Behav. Res. Ther.* 47, 761–773 (2009).
- Espinosa, L., Singh, L., Eimer, T., Olsson, A. & Holmes, E. A. Reading others' social appraisals after viewing an aversive film online impacts mood but not intrusive memories. *J. Anxiety Disord.* **99**, 102763 (2023).
- 54. Woud, M. L., Postma, P., Holmes, E. A. & Mackintosh, B. Reducing analogue trauma symptoms by computerized reappraisal training – considering a cognitive prophylaxis? *J. Behav. Ther. Exp. Psychiatry* **44**, 312–315 (2013).
- Lang, T. J., Moulds, M. L. & Holmes, E. A. Reducing depressive intrusions via a computerized cognitive bias modification of appraisals task: developing a cognitive vaccine. *Behav. Res. Ther.* 47, 139–145 (2009).
- 56. Würtz, F. et al. Using cognitive bias modification-appraisal training to manipulate appraisals about the self and the world in analog trauma. *Cogn. Ther. Res.* **46**, 232–246 (2022).
- 57. Woud, M. L. et al. The effects of modifying dysfunctional appraisals in posttraumatic stress disorder using a form of cognitive bias modification: results of a randomized controlled trial in an inpatient setting. *Psychother. Psychosom.* **90**, 386–402 (2021).
- van Schie, K., van Veen, S. C. & Hagenaars, M. A. The effects of dual-tasks on intrusive memories following analogue trauma. *Behav. Res. Ther.* **120**, 103448 (2019).
- Kleim, B., Wysokowsky, J., Schmid, N., Seifritz, E. & Rasch, B. Effects of sleep after experimental trauma on intrusive emotional memories. *Sleep* **39**, 2125–2132 (2016).
- 60. Zeng, S., Lin, X., Wang, J. & Hu, X. Sleep's short-term memory preservation and long-term affect depotentiation effect in emotional memory consolidation: behavioral and EEG evidence. *Sleep* **44**, zsab155 (2021).
- 61. Harrington, M. O. & Cairney, S. A. Sleep loss gives rise to intrusive thoughts. *Trends Cogn. Sci.* **25**, 434–436 (2021).
- Hu, X., Bergström, Z. M., Gagnepain, P. & Anderson, M. C. Suppressing unwanted memories reduces their unintended influences. *Curr. Dir. Psychol. Sci.* 26, 197–206 (2017).
- 63. Poh, J.-H., Chong, P. L. & Chee, M. W. Sleepless night, restless mind: effects of sleep deprivation on mind wandering. *J. Exp. Psychol. Gen.* **145**, 1312–1318 (2016).
- 64. van der Helm, E., Gujar, N. & Walker, M. P. Sleep deprivation impairs the accurate recognition of human emotions. *Sleep* **33**, 335–342 (2010).
- Van Someren, E. J. W. Brain mechanisms of insomnia: new perspectives on causes and consequences. *Physiol. Rev.* **101**, 995–1046 (2021).
- Holmes, E. A. et al. The Lancet Psychiatry Commission on psychological treatments research in tomorrow's science. *Lancet Psychiatry* 5, 237–286 (2018).
- Buckley, T. C., Holohan, D. R., Mozley, S. L., Walsh, K. & Kassel, J. The effect of nicotine and attention allocation on physiological and self-report measures of induced anxiety in PTSD: a double-blind placebo-controlled trial. *Exp. Clin. Psychopharmacol.* **15**, 154–164 (2007).
- Eckstein, M. et al. Oxytocin facilitates the sensation of social stress. Hum. Brain Mapp. 35, 4741–4750 (2014).
- Hawkins, K. A. & Cougle, J. R. The effects of nicotine on intrusive memories in nonsmokers. *Exp. Clin. Psychopharmacol.* 21, 434–442 (2013).
- Schultebraucks, K. et al. Heightened biological stress response during exposure to a trauma film predicts an increase in intrusive memories. J. Abnorm. Psychol. **128**, 645–657 (2019).

- Gonzalez-Perez, M., Wakui, E., Thoma, V., Nitsche, M. A. & Rivolta, D. Transcranial alternating current stimulation (tACS) at 40 Hz enhances face and object perception. *Neuropsychologia* 135, 107237 (2019).
- 72. Corlier, J. et al. Effect of repetitive transcranial magnetic stimulation (rTMS) treatment of major depressive disorder (MDD) on cognitive control. *J. Affect. Disord.* **265**, 272–277 (2020).
- 73. Diefenbach, G. J., Assaf, M., Goethe, J. W., Gueorguieva, R. & Tolin, D. F. Improvements in emotion regulation following repetitive transcranial magnetic stimulation for generalized anxiety disorder. J. Anxiety Disord. **43**, 1–7 (2016).
- 74. Voss, M., Ehring, T. & Wolkenstein, L. Does transcranial direct current stimulation affect post-stressor intrusive memories and rumination? An experimental analogue study. *Cogn. Ther. Res.* **43**, 535–549 (2019).
- 75. Herz, N. et al. Neuromodulation of visual cortex reduces the intensity of intrusive memories. *Cereb. Cortex* **32**, 408–417 (2022).
- Deforges, C., Fort, D., Stuijfzand, S., Holmes, E. A. & Horsch, A. Reducing childbirth-related intrusive memories and PTSD symptoms via a single-session behavioural intervention including a visuospatial task: a proof-of-principle study. J. Affect. Disord. **303**, 64–73 (2022).
- Deforges, C. et al. Single-session visuospatial task procedure to prevent childbirth-related posttraumatic stress disorder: a multicentre double-blind randomised controlled trial. *Mol. Psychiatry* 28, 3842–3850 (2023).
- Horsch, A. et al. Reducing intrusive traumatic memories after emergency caesarean section: a proof-of-principle randomized controlled study. *Behav. Res. Ther.* 94, 36–47 (2017).
- 79. Iyadurai, L. et al. Preventing intrusive memories after trauma via a brief intervention involving Tetris computer game play in the emergency department: a proof-of-concept randomized controlled trial. *Mol. Psychiatry* **23**, 674–682 (2018).
- Ramineni, V. et al. Treating intrusive memories after trauma in healthcare workers: a Bayesian adaptive randomised trial developing an imagery-competing task intervention. *Mol. Psychiatry* 28, 2985–2994 (2023).
- 81. Kanstrup, M. et al. A single case series using visuospatial task interference to reduce the number of visual intrusive memories of trauma with refugees. *Clin. Psychol. Psychother.* **28**, 109–123 (2021).
- 82. van Emmerik, A. A. P., Kamphuis, J. H., Hulsbosch, A. M. & Emmelkamp, P. M. G. Single session debriefing after psychological trauma: a meta-analysis. *Lancet* **360**, 766–771 (2002).
- Stileman, H. M. & Jones, C. A. Revisiting the debriefing debate: does psychological debriefing reduce PTSD symptomology following work-related trauma? A meta-analysis. *Front. Psychol.* 14, 1248924 (2023).
- 84. Badawi, A., Steel, Z., Mahoney, C. & Berle, D. Feasibility of an adjunctive cognitive task in the treatment of posttraumatic stress disorder. *Discov. Psychol.* **1**, 11 (2021).
- 85. Arendt, I.-M. T., Riisager, L. H., Larsen, J. E., Christiansen, T. B. & Moeller, S. B. Distinguishing between rumination and intrusive memories in PTSD using a wearable self-tracking instrument: a proof-of-concept case study. *Cogn. Behav. Ther.* **14**, e15 (2021).
- Dalgleish, T. & Hitchcock, C. Transdiagnostic distortions in autobiographical memory recollection. *Nat. Rev. Psychol.* 2, 166–182 (2023).
- Ehlers, A. & Steil, R. Maintenance of intrusive memories in posttraumatic stress disorder: a cognitive approach. *Behav. Cogn. Psychother.* 23, 217–249 (1995).
- Holmes, E. A. & Mathews, A. Mental imagery in emotion and emotional disorders. *Clin. Psychol. Rev.* 30, 349–362 (2010).

- 89. Macatee, R. J. et al. Shared and distinct cognitive/affective mechanisms in intrusive cognition: an examination of worry and obsessions. *Cogn. Ther. Res.* **40**, 80–91 (2016).
- 90. van Bentum, J. S. et al. Treating repetitive suicidal intrusions using eye movements: study protocol for a multicenter randomized clinical trial. *BMC Psychiatry* **19**, 143 (2019).
- McShane, B. B. & Böckenholt, U. Multilevel multivariate meta-analysis made easy: an introduction to MLMVmeta. *Behav. Res. Methods* 55, 2367–2386 (2022).
- Higgins, J. P. T., Lasserson, T., Thomas, J., Flemyng, E. & Churchill, R. Methodological Expectations of Cochrane Intervention Reviews (Cochrane, 2023).
- Moher, D., Liberati, A., Tetzlaff, J., Altman, D. & PRISMA Group. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *Ann. Intern. Med.* 151, 264–269 (2009).
- Zeng, S., Varma, M. M., Chiu, M. H. & Hu, X. A systematic review and meta-analysis of experimental methods for modulating intrusive memories following lab-analogue trauma exposure in non-clinical populations. OSF https://osf.io/phu7w/ (2024).
- 95. Wells, A. & Papageorgiou, C. Worry and the incubation of intrusive images following stress. *Behav. Res. Ther.* **33**, 579–583 (1995).
- Murray, J. The Role of Dissociation in the Development and Maintenance of Post-traumatic Stress Disorder. PhD thesis, Univ. of Oxford (1997).
- Lepore, S. J., Ragan, J. D. & Jones, S. Talking facilitates cognitiveemotional processes of adaptation to an acute stressor. *J. Pers.* Soc. Psychol. **78**, 499–508 (2000).
- Brewin, C. R. & Saunders, J. The effect of dissociation at encoding on intrusive memories for a stressful film. *Br. J. Med. Psychol.* 74, 467–472 (2001).
- Halligan, S. L., Clark, D. M. & Ehlers, A. Cognitive processing, memory, and the development of PTSD symptoms: two experimental analogue studies. J. Behav. Ther. Exp. Psychiatry 33, 73–89 (2002).
- 100. Stuart, A. Dissociation and Later Intrusive Memories. PhD thesis, Univ. College London (2002).
- 101. Frasquilho, F. M. The Role of Peri-traumatic Visuo-spatial and Verbal Interference on the Development of Intrusions. PhD thesis, Univ. of London (2004).
- 102. Turl, E. J. Threat Monitoring and the Development of Symptoms of Posttraumatic Stress Disorder. PhD thesis, Univ. of Manchester (2005).
- 103. Michael, T. & Ehlers, A. Enhanced perceptual priming for neutral stimuli occurring in a traumatic context: two experimental investigations. *Behav. Res. Ther.* **45**, 341–358 (2007).
- 104. Nixon, R. D., Nehmy, T. & Seymour, M. The effect of cognitive load and hyperarousal on negative intrusive memories. *Behav. Res. Ther.* 45, 2652–2663 (2007).
- 105. Postma, P. The Effects of Training an Interpretation Bias on Later Intrusive Recollection in an Analogue Study of Post Traumatic Stress Disorder. PhD thesis, Univ. of East Anglia (2007).
- 106. Kindt, M., van den Hout, M., Arntz, A. & Drost, J. The influence of data-driven versus conceptually-driven processing on the development of PTSD-like symptoms. *J. Behav. Ther. Exp. Psychiatry* **39**, 546–557 (2008).
- 107. Bisby, J. A., Brewin, C. R., Leitz, J. R. & Valerie Curran, H. Acute effects of alcohol on the development of intrusive memories. *Psychopharmacology* **204**, 655–666 (2009).
- 108. Ehring, T., Szeimies, A.-K. & Schaffrick, C. An experimental analogue study into the role of abstract thinking in trauma-related rumination. *Behav. Res. Ther.* **47**, 285–293 (2009).
- 109. Krans, J., Näring, G. & Becker, E. S. Count out your intrusions: effects of verbal encoding on intrusive memories. *Memory* 17, 809–815 (2009).

- 110. Krans, J., Näring, G., Holmes, E. A. & Becker, E. S. Tell me more: can a memory test reduce analogue traumatic intrusions? *Behav. Res. Ther.* **47**, 426–430 (2009).
- Nixon, R. D. V., Cain, N., Nehmy, T. & Seymour, M. Does post-event cognitive load undermine thought suppression and increase intrusive memories after exposure to an analogue stressor? *Memory* 17, 245–255 (2009).
- Nixon, R. D., Cain, N., Nehmy, T. & Seymour, M. The influence of thought suppression and cognitive load on intrusions and memory processes following an analogue stressor. *Behav. Ther.* 40, 368–379 (2009).
- Zetsche, U., Ehring, T. & Ehlers, A. The effects of rumination on mood and intrusive memories after exposure to traumatic material: an experimental study. J. Behav. Ther. Exp. Psychiatry 40, 499–514 (2009).
- 114. Bisby, J. A., King, J. A., Brewin, C. R., Burgess, N. & Curran, H. V. Acute effects of alcohol on intrusive memory development and viewpoint dependence in spatial memory support a dual representation model. *Biol. Psychiatry* **68**, 280–286 (2010).
- 115. Holmes, E. A., James, E. L., Kilford, E. J. & Deeprose, C. Key steps in developing a cognitive vaccine against traumatic flashbacks: visuospatial Tetris versus verbal Pub Quiz. *PLoS ONE* **5**, e13706 (2010).
- Krans, J., Näring, G., Holmes, E. A. & Becker, E. S. Motion effects on intrusion development. *J. Trauma Dissociation* **11**, 73–82 (2010).
- Pearson, D. G. & Sawyer, T. Effects of dual task interference on memory intrusions for affective images. *Int. J. Cogn. Ther.* 4, 122–133 (2011).
- 118. Ball, S. C. & Brewin, C. R. The effect of rumination on intrusive images and mood: an experimental investigation using the trauma film. *Paradig. J. Exp. Psychopathol.* **3**, 297–309 (2012).
- 119. Bittinger, J. N. Retrieval-Induced Forgetting: A Proposed Mechanism for Intrusive Reexperiencing in Posttraumatic Stress Disorder. PhD thesis, Univ. of Washington (2012).
- 120. Brown, A. D., Joscelyne, A., Dorfman, M. L., Marmar, C. R. & Bryant, R. A. The impact of perceived self-efficacy on memory for aversive experiences. *Memory* **20**, 374–383 (2012).
- 121. Deeprose, C., Zhang, S., DeJong, H., Dalgleish, T. & Holmes, E. A. Imagery in the aftermath of viewing a traumatic film: using cognitive tasks to modulate the development of involuntary memory. J. Behav. Ther. Exp. Psychiatry **43**, 758–764 (2012).
- 122. Ehlers, A., Mauchnik, J. & Handley, R. Reducing unwanted trauma memories by imaginal exposure or autobiographical memory elaboration: an analogue study of memory processes. *J. Behav. Ther. Exp. Psychiatry* **43**, S67–S75 (2012).
- Hagenaars, M. A. Anxiety symptoms influence the effect of posttrauma interventions after analogue trauma. J. Exp. Psychopathol.
 3, 209–222 (2012).
- 124. Hagenaars, M. A. & Arntz, A. Reduced intrusion development after post-trauma imagery rescripting; an experimental study. *J. Behav. Ther. Exp. Psychiatry* **43**, 808–814 (2012).
- 125. Krans, J. & Bos, M. W. To think or not to think about trauma? An experimental investigation into unconscious thought and intrusion development. J. Exp. Psychopathol. **3**, 310–321 (2012).
- 126. Pearson, D. G. Contextual representations increase analogue traumatic intrusions: evidence against a dual-representation account of peri-traumatic processing. *J. Behav. Ther. Exp. Psychiatry* **43**, 1026–1031 (2012).
- 127. Verwoerd, J., Wessel, I. & De Jong, P. J. Fewer intrusions after an attentional bias modification training for perceptual reminders of analogue trauma. *Cogn. Emot.* **26**, 153–165 (2012).
- 128. Warnock, K. The Role of Rumination in Ptsd Symptom Maintenance: an Analogue Study. PhD thesis, King's College London (2012).

- 129. Bryant, R. A., McGrath, C. & Felmingham, K. L. The roles of noradrenergic and glucocorticoid activation in the development of intrusive memories. *PLoS ONE* **8**, e62675 (2013).
- Cheung, J., Chervonsky, L., Felmingham, K. L. & Bryant, R. A. The role of estrogen in intrusive memories. *Neurobiol. Learn. Mem.* 106, 87–94 (2013).
- 131. Krans, J. The self and involuntary memory: identifying with the victim increases memory accessibility for stressful events. *Conscious. Cogn.* **22**, 1298–1304 (2013).
- 132. Krans, J., Janecko, D. & Bos, M. W. Unconscious thought reduces intrusion development: a replication and extension. J. Behav. Ther. Exp. Psychiatry 44, 179–185 (2013).
- 133. Krans, J., Langner, O., Reinecke, A. & Pearson, D. G. Intrusive images and voluntary memory for affective pictures: contextualization and dual-task interference. *J. Behav. Ther. Exp. Psychiatry* 44, 418–425 (2013).
- 134. Schaich, A., Watkins, E. R. & Ehring, T. Can concreteness training buffer against the negative effects of rumination on PTSD? An experimental analogue study. J. Behav. Ther. Exp. Psychiatry 44, 396–403 (2013).
- 135. Marks, E. H. & Zoellner, L. A. Attenuating fearful memories: effect of cued extinction on intrusions. *Emotion* **14**, 1143–1154 (2014).
- 136. Polack, R. E. L. R. The Effect of Viewpoint Dependence in Spatial Memory Tasks on Intrusive Memories in Analogue Trauma. PhD thesis, Univ. College London (2014).
- 137. Takarangi, M. K. T., Segovia, D. A., Dawson, E. & Strange, D. Emotional impact feedback affects how people remember an analogue trauma event. *Memory* 22, 1041–1051 (2014).
- 138. Wells, A. & Roussis, P. Refraining from intrusive thoughts is strategy dependent: a comment on Sugiura, et al. and a preliminary informal test of detached mindfulness, acceptance, and other strategies. *Psychol. Rep.* **115**, 541–544 (2014).
- 139. Cheung, J., Garber, B. & Bryant, R. A. The role of stress during memory reactivation on intrusive memories. *Neurobiol. Learn. Mem.* **123**, 28–34 (2015).
- 140. Gittins, C. B., Paterson, H. M. & Sharpe, L. How does immediate recall of a stressful event affect psychological response to it? J. Behav. Ther. Exp. Psychiatry 46, 19–26 (2015).
- 141. Kubota, R., Nixon, R. D. V. & Chen, J. Trauma-related rumination mediates the effect of naturally occurring depressive symptoms but not momentary low mood on trauma intrusions. *Aust. J. Psychol.* 67, 75–86 (2015).
- 142. Pile, V., Barnhofer, T. & Wild, J. Updating versus exposure to prevent consolidation of conditioned fear. *PLoS ONE* **10**, e0122971 (2015).
- 143. Porcheret, K., Holmes, E. A., Goodwin, G. M., Foster, R. G. & Wulff, K. Psychological effect of an analogue traumatic event reduced by sleep deprivation. *Sleep* **38**, 1017–1025 (2015).
- 144. Bryant, R. A. & Foord, R. Activating attachments reduces memories of traumatic images. *PLoS ONE* **11**, e0162550 (2016).
- 145. Das, R. K. et al. Nitrous oxide speeds the reduction of distressing intrusive memories in an experimental model of psychological trauma. *Psychol. Med.* **46**, 1749–1759 (2016).
- 146. Dibbets, P. & Arntz, A. Imagery rescripting: is incorporation of the most aversive scenes necessary? *Memory* **24**, 683–695 (2016).
- 147. Dorahy, M. J., Peck, R. K. & Huntjens, R. J. C. The impact of dissociation on perceptual priming and intrusions after listening to auditory narratives. *J. Trauma Dissociation* **17**, 410–425 (2016).
- 148. James, E. L., Lau-Zhu, A., Tickle, H., Horsch, A. & Holmes, E. A. Playing the computer game Tetris prior to viewing traumatic film material and subsequent intrusive memories: examining proactive interference. *J. Behav. Ther. Exp. Psychiatry* **53**, 25–33 (2016).
- 149. Krans, J., Pearson, D. G., Maier, B. & Moulds, M. L. Contextual representations of negative images modulate intrusion frequency in an intrusion provocation paradigm. *J. Behav. Ther. Exp. Psychiatry* 53, 52–58 (2016).

- 150. Rombold, F. et al. Influence of the noradrenergic system on the formation of intrusive memories in women: an experimental approach with a trauma film paradigm. *Psychol. Med.* **46**, 2523–2534 (2016).
- 151. Rombold, F. et al. Impact of exogenous cortisol on the formation of intrusive memories in healthy women. *J. Psychiatr. Res.* **83**, 71–78 (2016).
- 152. Segovia, D. A., Strange, D. & Takarangi, M. K. Encoding disorganized memories for an analogue trauma does not increase memory distortion or analogue symptoms of PTSD. J. Behav. Ther. Exp. Psychiatry 50, 127–134 (2016).
- 153. Tabrizi, F. & Jansson, B. Reducing involuntary memory by interfering consolidation of stressful auditory information: a pilot study. J. Behav. Ther. Exp. Psychiatry **50**, 238–244 (2016).
- 154. White, R. & Wild, J. "Why" or "How": the effect of concrete versus abstract processing on intrusive memories following analogue trauma. *Behav. Ther.* 47, 404–415 (2016).
- 155. Bryant, R. A. & Chan, I. Activating attachment representations during memory retrieval modulates intrusive traumatic memories. *Conscious. Cogn.* 55, 197–204 (2017).
- 156. Bub, K. & Lommen, M. J. J. The role of guilt in Posttraumatic Stress Disorder. *Eur. J. Psychotraumatol.* **8**, 1407202 (2017).
- 157. Cheung, J. & Bryant, R. A. The impact of appraisals on intrusive memories. J. Behav. Ther. Exp. Psychiatry **54**, 108–111 (2017).
- 158. Graebener, A. H., Michael, T., Holz, E. & Lass-Hennemann, J. Repeated cortisol administration does not reduce intrusive memories – a double blind placebo controlled experimental study. *Eur. Neuropsychopharmacol.* 27, 1132–1143 (2017).
- 159. Keyan, D. & Bryant, R. A. Acute physical exercise in humans enhances reconsolidation of emotional memories. *Psychoneuroendocrinology* **86**, 144–151 (2017).
- 160. Keyan, D. & Bryant, R. A. Brief exercise enhances intrusive memories of traumatic stimuli. *Neurobiol. Learn. Mem.* 141, 9–13 (2017).
- 161. Kubota, R. & Nixon, R. D. V. An analogue investigation into the effect of trauma-related rumination on trauma intrusions and the moderating role of trait rumination and depression. J. Exp. Psychopathol. 8, 413–442 (2017).
- 162. Marks, E. H. Reducing Intrusive Memories of Real-world Stimuli Via Memory Reconsolidation. PhD thesis, Univ. of Washington (2018).
- 163. Page, S. & Coxon, M. Preventing post-traumatic intrusions using virtual reality. Annu. Rev. Cyberther. Telemed. 15, 129–134 (2017).
- 164. Ripley, A. J., Clapp, J. D. & Beck, J. G. A prospective examination of risk factors in the development of intrusions following a trauma analog. *Behav. Res. Ther.* **94**, 71–80 (2017).
- 165. Shepstone, L. L. Compassion-Facilitation After Trauma. PhD thesis, Univ. of Exeter (2017).
- 166. Streb, M., Conway, M. A. & Michael, T. Conditioned responses to trauma reminders: how durable are they over time and does memory integration reduce them? *J. Behav. Ther. Exp. Psychiatry* 57, 88–95 (2017).
- Woodward, M. J. & Beck, J. G. Using the trauma film paradigm to explore interpersonal processes after trauma exposure. *Psychol. Trauma Theory Res. Pract. Policy* **9**, 445–452 (2017).
- 168. Asselbergs, J. et al. Development and testing of TraumaGameplay: an iterative experimental approach using the trauma film paradigm. *Eur. J. Psychotraumatol.* **9**, 1424447 (2018).
- 169. Jaffe, A. E. Effects of Peritraumatic Alcohol Intoxication on Intrusive Memories Following Exposure to an Analog Trauma. PhD thesis, Univ. of Nebraska-Lincoln (2018).
- 170. Krans, J., Brown, A. D. & Moulds, M. L. Can an experimental self-efficacy induction through autobiographical recall modulate analogue posttraumatic intrusions? *J. Behav. Ther. Exp. Psychiatry* 58, 1–11 (2018).

- 171. Lass-Hennemann, J., Schäfer, S. K., Römer, S., Holz, E. & Michael, T. Therapy dogs as a crisis intervention after traumatic events? – An experimental study. *Front. Psychol.* 9, 386572 (2018).
- 172. Oulton, J. M., Strange, D., Nixon, R. D. & Takarangi, M. K. Imagining trauma: memory amplification and the role of elaborative cognitions. J. Behav. Ther. Exp. Psychiatry 60, 78–86 (2018).
- 173. Allen, C. E. Impact of Social Support during a Social Interaction on Post-trauma Cognitions and Outcomes during a Trauma Analogue Design. PhD thesis, Northern Illinois Univ. (2019).
- 174. Brühl, A., Heinrichs, N., Bernstein, E. E. & McNally, R. J. Preventive efforts in the aftermath of analogue trauma: the effects of Tetris and exercise on intrusive images. *J. Behav. Ther. Exp. Psychiatry* 64, 31–35 (2019).
- 175. Hørlyck, L. D., Bisby, J. A., King, J. A. & Burgess, N. Wakeful rest compared to vigilance reduces intrusive but not deliberate memory for traumatic videos. *Sci. Rep.* **9**, 13403 (2019).
- 176. Kuiling, J. M. E., Klaassen, F. & Hagenaars, M. A. The role of tonic immobility and control in the development of intrusive memories after experimental trauma. *Memory* 27, 772–779 (2019).
- Lau-Zhu, A., Henson, R. N. & Holmes, E. A. Intrusive memories and voluntary memory of a trauma film: differential effects of a cognitive interference task after encoding. *J. Exp. Psychol. Gen.* 148, 2154–2180 (2019).
- 178. Meyer, T., Ikani, N. & Morina, N. Spatio-temporal associations with memory cues are linked to analogue traumatic intrusions. *Behav. Res. Ther.* **123**, 103481 (2019).
- 179. Mooren, N., Krans, J., Näring, G. & van Minnen, A. Vantage perspective in analogue trauma memories: an experimental study. *Cogn. Emot.* **33**, 1261–1270 (2019).
- 180. Porcheret, K. et al. Investigation of the impact of total sleep deprivation at home on the number of intrusive memories to an analogue trauma. *Transl. Psychiatry* **9**, 104 (2019).
- Rahman, N. et al. Increasing self-efficacy reduces visual intrusions to a trauma-film paradigm. *Anxiety Stress Coping* **32**, 202–215 (2019).
- Scheele, D. et al. Trauma disclosure moderates the effects of oxytocin on intrusions and neural responses to fear. *Psychother. Psychosom.* 88, 61–63 (2019).
- 183. Siegesleitner, M., Strohm, M., Wittekind, C. E., Ehring, T. & Kunze, A. E. Effects of imagery rescripting on consolidated memories of an aversive film. *J. Behav. Ther. Exp. Psychiatry* 62, 22–29 (2019).
- 184. Sopp, M. R., Brueckner, A. H., Schäfer, S. K., Lass-Hennemann, J. & Michael, T. Differential effects of sleep on explicit and implicit memory for potential trauma reminders: findings from an analogue study. *Eur. J. Psychotraumatol.* **10**, 1644128 (2019).
- Woud, M. L. et al. Investigating the effect of proactive interference control training on intrusive memories. *Eur. J. Psychotraumatol.* 10, 1611092 (2019).
- 186. Badawi, A., Berle, D., Rogers, K. & Steel, Z. Do cognitive tasks reduce intrusive-memory frequency after exposure to analogue trauma? An experimental replication.*Clin. Psychol. Sci.* 8, 569–583 (2020).
- Elsey, J. W., Bekker, T. A., De Bree, A. M. & Kindt, M. Encoding or consolidation? The effects of pre-and post-learning propranolol on the impact of an emotional scene. *J. Behav. Ther. Exp. Psychiatry* 67, 101480 (2020).
- 188. Kamboj, S. K. et al. Reduction in the occurrence of distressing involuntary memories following propranolol or hydrocortisone in healthy women. *Psychol. Med.* **50**, 1148–1155 (2020).
- 189. Kessler, H. et al. Visuospatial computer game play after memory reminder delivered three days after a traumatic film reduces the number of intrusive memories of the experimental trauma. J. Behav. Ther. Exp. Psychiatry 67, 101454 (2020).

- 190. Kubota, R. & Nixon, R. D. V. The effect of mindfulness training on rumination and intrusions after analogue trauma. *Aust. Psychol.* 55, 108–120 (2020).
- 191. Meyer, T. et al. Arresting visuospatial stimulation is insufficient to disrupt analogue traumatic intrusions. *PLoS ONE* **15**, e0228416 (2020).
- Nagulendran, A., Norton, P. J. & Jobson, L. Investigating cultural differences in the effects of expressive suppression when processing traumatic distressing material. *Behav. Cogn. Psychother.* 48, 658–671 (2020).
- 193. Rijkeboer, M. M., Daemen, J. J., Flipse, A., Bouwman, V. & Hagenaars, M. A. Rescripting experimental trauma: effects of imagery and writing as a way to reduce the development of intrusive memories. J. Behav. Ther. Exp. Psychiatry 67, 101478 (2020).
- 194. Shkreli, L. et al. Angiotensin involvement in trauma processing exploring candidate neurocognitive mechanisms of preventing post-traumatic stress symptoms. *Neuropsychopharmacology* **45**, 507–514 (2020).
- 195. Siegesleitner, M., Strohm, M., Wittekind, C. E., Ehring, T. & Kunze, A. E. Improving imagery rescripting treatments: comparing an active versus passive approach. *J. Behav. Ther. Exp. Psychiatry* **69**, 101578 (2020).
- 196. Brennen, T. et al. Investigating the frequency of intrusive memories after 24 hours using a visuospatial interference intervention: a follow-up and extension. *Eur. J. Psychotraumatol.* 12, 1953788 (2021).
- Franke, L. K. et al. Intrusive memories as conditioned responses to trauma cues: an empirically supported concept? *Behav. Res. Ther.* 143, 103848 (2021).
- 198. Guzey, M., Funk, J., Kustermann, J. & Ehring, T. The effect of concreteness training on peri-traumatic processing and intrusive memories following an analogue trauma. *Behav. Res. Ther.* **147**, 103970 (2021).
- 199. Karl, A. et al. The effect of attachment security priming and oxytocin on physiological responses to trauma films and subsequent intrusions. *Behav. Res. Ther.* **141**, 103845 (2021).
- 200. Lau-Zhu, A., Henson, R. N. & Holmes, E. A. Selectively interfering with intrusive but not voluntary memories of a trauma film: accounting for the role of associative memory. *Clin. Psychol. Sci.* 9, 1128–1143 (2021).
- 201. Nguyen, A. M. Effects of Intrusive Symptoms and Emotional Reactivity in a Laboratory-Based Film Analog Study. PhD thesis, Univ. of Arkansas (2021).
- 202. Sopp, M. R. et al. Wakefulness impairs selective consolidation of relevant trauma-associated memories resulting in more frequent intrusions. *Behav. Res. Ther.* **136**, 103776 (2021).
- 203. Wilhelm, I. et al. Investigating the effect of a nap following experimental trauma on analogue PTSD symptoms. *Sci. Rep.* **11**, 4710 (2021).
- 204. Zeng, S., Lau, E. Y. Y., Li, S. X. & Hu, X. Sleep differentially impacts involuntary intrusions and voluntary recognitions of lab-analogue traumatic memories. *J. Sleep Res.* **30**, e13208 (2021).
- 205. Espinosa, L., Bonsall, M. B., Becker, N., Holmes, E. A. & Olsson, A. Pavlovian threat conditioning can generate intrusive memories that persist over time. *Behav. Res. Ther.* **157**, 104161 (2022).
- 206. Hennessy, V. E., Troebinger, L., Iskandar, G., Das, R. K. & Kamboj, S. K. Accelerated forgetting of a trauma-like event in healthy men and women after a single dose of hydrocortisone. *Transl. Psychiatry* **12**, 354 (2022).
- 207. Herzog, P., Barth, C., Rief, W., Brakemeier, E.-L. & Kube, T. How expectations shape the formation of intrusive memories: an experimental study using the trauma film paradigm. *Cogn. Ther. Res.* **46**, 809–826 (2022).

Article

- 208. Hilberdink, C. E., de Rooij, S. R., Olff, M., Bosch, J. A. & van Zuiden, M. Acute stress reactivity and intrusive memory development: a randomized trial using an adjusted trauma film paradigm. *Psychoneuroendocrinology* **139**, 105686 (2022).
- 209. Hoffman, J. & Nickerson, A. An experimental investigation of the impact of blame appraisals and moral injury beliefs on psychological outcomes. *Cogn. Ther. Res.* **46**, 319–332 (2022).
- Jones, P. J. & McNally, R. J. Does broadening one's concept of trauma undermine resilience? *Psychol. Trauma Theory Res. Pract. Policy* 14, S131 (2022).
- 211. Kube, T., Kirsch, I., Glombiewski, J. A. & Herzog, P. Can placebos reduce intrusive memories? *Behav. Res. Ther.* **158**, 104197 (2022).
- 212. Meyer, T. & Morina, N. Social comparison modulates acute responses to traumatic footage and the development of intrusive memories. J. Exp. Psychopathol. **13**, 204380872210758 (2022).
- 213. Schultebraucks, K. et al. Intranasal oxytocin administration impacts the acquisition and consolidation of trauma-associated memories: a double-blind randomized placebo-controlled experimental study in healthy women. *Neuropsychopharmacology* **47**, 1046–1054 (2022).
- 214. Woodward, M. J., Clapp, J. D., Cotney, S. E. & Beck, J. G. Interacting with a friend after a trauma film reduces anxiety and intrusive memories. *Psychol. Trauma* **16**, 759–767 (2022).
- 215. Friesen, E., Sopp, M. R., Cordi, M. J., Rasch, B. & Michael, T. Sleep-directed hypnosis improves subjective sleep quality but not extinction memory after exposure to analog trauma. *Cogn. Ther. Res.* 47, 255–268 (2023).
- 216. Gvozdanovic, G., Schoch, S., Stämpfli, P., Seifritz, E. & Rasch, B. Neural correlates of sleep-induced benefits on traumatic memory processing. *Hum. Brain Mapp.* 44, 3506–3518 (2023).
- 217. Hemi, A., Sopp, M. R., Perel, A., Holmes, E. A. & Levy-Gigi, E. Cognitive flexibility moderates the efficacy of a visuospatial intervention following exposure to analog trauma. *J. Behav. Ther. Exp. Psychiatry* **81**, 101858 (2023).
- 218. Li, C., Otgaar, H., Battista, F., Muris, P. & Wang, J. Challenging memories reduces intrusive memories and the memory amplification effect. *Memory* **31**, 1039–1050 (2023).
- 219. Maslahati, T. et al. Oxytocin vs. placebo effects on intrusive memory consolidation using a trauma film paradigm: a randomized, controlled experimental study in healthy women. *Transl. Psychiatry* **13**, 42 (2023).
- 220. Xu, Z., Hu, J. & Wang, Y. Bilateral eye movements disrupt the involuntary perceptual representation of trauma-related memories. *Behav. Res. Ther.* **165**, 104311 (2023).
- 221. Asselbergs, J., Riper, H., Engelhard, I. M., Mannes, F. & Sijbrandij, M. The effectiveness of two novel approaches to prevent intrusions: a pilot study comparing Tetris_dualtask and imagery rescripting to control. J. Behav. Ther. Exp. Psychiatry 82, 101920 (2024).
- 222. Horowitz, M., Wilner, N. & Alvarez, W. Impact of event scale: a measure of subjective stress. *Psychosom. Med.* **41**, 209–218 (1979).
- 223. Weiss, D. & Marmar, C. in Assessing Psychological Trauma and PTSD: A Handbook for Practitioners (eds Wilson J. P. & Keane T. M.) 399–411 (Guilford Press, 2004).
- 224. Das, R. K., Freeman, T. P. & Kamboj, S. K. The effects of *N*-methyl D-aspartate and B-adrenergic receptor antagonists on the reconsolidation of reward memory: a meta-analysis. *Neurosci. Biobehav. Rev.* **37**, 240–255 (2013).
- 225. Hedges, L. V. Distribution theory for Glass's estimator of effect size and related estimators. *J. Educ. Stat.* **6**, 107–128 (1981).
- 226. R Core Team. R: A Language and Environment for Statistical Computing. https://www.r-project.org/ (R Foundation for Statistical Computing, 2013).
- 227. Viechtbauer, W. Conducting meta-analyses in R with the metafor package. J. Stat. Softw. **36**, 1–48 (2010).

- 228. Lüdecke, D. esc: Effect Size Computation for Meta Analysis (Version 0.5.1). R package version 05 https://doi.org/10.5281/ zenodo.1249218 (2019).
- 229. Cheung, M. W.-L. Modeling dependent effect sizes with three-level meta-analyses: a structural equation modeling approach. *Psychol. Methods* **19**, 211–229 (2014).
- 230. Harrer, M., Cuijpers, P., Furukawa, T. & Ebert, D. Doing Meta-Analysis with R: A Hands-On Guide (Chapman and Hall/CRC, 2021).
- 231. Peters, J. L., Sutton, A. J., Jones, D. R., Abrams, K. R. & Rushton, L. Contour-enhanced meta-analysis funnel plots help distinguish publication bias from other causes of asymmetry. *J. Clin. Epidemiol.* **61**, 991–996 (2008).
- Egger, M., Smith, G. D., Schneider, M. & Minder, C. Bias in meta-analysis detected by a simple, graphical test. *Brit. Med. J.* 315, 629–634 (1997).
- 233. Duval, S. & Tweedie, R. Trim and fill: a simple funnel-plot-based method of testing and adjusting for publication bias in metaanalysis. *Biometrics* **56**, 455–463 (2000).
- 234. Iyengar, S. & Greenhouse, J. B. Selection models and the file drawer problem. *Stat. Sci.* **3**, 109–135 (1988).

Acknowledgements

The research was supported by the Ministry of Science and Technology of China STI2030-Major Projects (No. 2022ZD0214100, X.H.), the National Natural Science Foundation of China (No. 32171056, X.H.), the General Research Fund (No. 17614922, X.H.) of the Hong Kong Research Grants Council, and the Swedish Research Council (2020-00873, E.A.H.). The funders had no role in study design, data collection and analysis, decision to publish or preparation of the manuscript. We thank our lab interns for their time in double-checking the coding and in helping improve the meta-analysis websites. We also thank the researchers who generously shared their data with us.

Author contributions

M.M.V. and S.Z. conceptualized the project, conducted investigations and formal analysis, curated data, developed the methodology and software, performed validation and visualization, wrote the original draft, and reviewed and edited the manuscript. L.S. conducted investigations, formal analysis and validation, and reviewed and edited the manuscript. E.A.H. conducted formal analysis, and reviewed and edited the manuscript. J.H. and M.H.C. conducted formal analysis and validation, and developed software. X.H. conceptualized the project, conducted investigations and formal analysis, curated data, performed validation, wrote the original draft, reviewed and edited the manuscript, administered and supervised the project, and acquired funding.

Competing interests

E.A.H.'s salary was partly funded by the Wellcome Trust (223016/Z/21/Z) via consultancy to P1vital Products Ltd for a different study. E.A.H. also receives funding from the Oak Foundation (OCAY-18-442) and Rannís The Icelandic Research Fund. E.A.H. developed the imagery-competing task intervention for intrusive memories, and know-how and training in using it over the past 20 years (ANEMONE). E.A.H. receives book royalties from Guildford Press and Oxford University Press, receives occasional honoraria for conference keynotes and clinical workshops and is on the Board of Trustees of the MQ Foundation. L.S. is an employee of Tobii AB since 2023. The remaining authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41562-024-01956-y.

Correspondence and requests for materials should be addressed to Xiaoqing Hu.

Peer review information *Nature Human Behaviour* thanks Kirsi Peltonen and Sarah Schäfer for their contribution to the peer review of this work.

Reprints and permissions information is available at www.nature.com/reprints.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by-nc-nd/4.0/.

© The Author(s) 2024

¹Department of Management, Marketing, and Information Systems, Hong Kong Baptist University, Hong Kong SAR, China. ²Department of Psychology, The University of Hong Kong, Hong Kong SAR, China. ³The State Key Lab of Brain and Cognitive Sciences, The University of Hong Kong, Hong Kong SAR, China. ⁴Department of Psychiatry, Beth Israel Deaconess Medical Center, Boston, MA, USA. ⁵Department of Psychiatry, Harvard Medical School, Boston, MA, USA. ⁶Department of Psychology, Uppsala University, Uppsala, Sweden. ⁷Swedish Collegium for Advanced Study, Uppsala, Sweden. ⁸Department of Women's and Children's Health, Uppsala University, Uppsala, Sweden. ⁹School of Computer Science and Engineering, Sun Yat-sen University, Guangzhou, China. ¹⁰HKU-Shenzhen Institute of Research and Innovation, Shenzhen, China. ¹¹These authors contributed equally: Mohith M. Varma, Shengzi Zeng. —email: xiaoqinghu@hku.hk

nature portfolio

Corresponding author(s): Xiaoqing Hu

Last updated by author(s): Jul 12, 2024

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our <u>Editorial Policies</u> and the <u>Editorial Policy Checklist</u>.

Statistics

For	all st	atistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.
n/a	Cor	firmed
	\square	The exact sample size (n) for each experimental group/condition, given as a discrete number and unit of measurement
	\square	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
		The statistical test(s) used AND whether they are one- or two-sided Only common tests should be described solely by name; describe more complex techniques in the Methods section.
		A description of all covariates tested
	\square	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
		A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
		For null hypothesis testing, the test statistic (e.g. F, t, r) with confidence intervals, effect sizes, degrees of freedom and P value noted Give P values as exact values whenever suitable.
\ge		For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
	\square	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
	\square	Estimates of effect sizes (e.g. Cohen's d, Pearson's r), indicating how they were calculated
		Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

 Policy information about availability of computer code

 Data collection
 This meta-analysis synthesized data extracted from existing datasets and research articles. We used Microsoft Excel (version 16.76) to input and organize data.

 Data analysis
 We used Microsoft Excel (version 16.76), R (R Core Team, 2020, version 4.2.2, 2022-10-31),metafor (Viechtbauer, 2010, 3.0-2, 2021-06-09) for data analyses.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a <u>data availability statement</u>. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

All data and scripts are available in the Open Science Framework (OSF: https://osf.io/phu7w).

Research involving human participants, their data, or biological material

Policy information about studies with <u>human participants or human data</u>. See also policy information about <u>sex, gender (identity/presentation),</u> and sexual orientation and <u>race, ethnicity and racism</u>.

Reporting on sex and gender	We reported gender information and results related to gender effect. We provided the source data containing gender information.
Reporting on race, ethnicity, or other socially relevant groupings	We reported continent/country/region from which the data were collected. Information on race, ethnicity and other socially relevant groupings were provided in each research article.
Population characteristics	We reported gender, age, continent/country/region from which the data were collected. We included studies that pre- screened participants based on history of psychiatric disorders.
Recruitment	This meta-analysis synthesized data extracted from existing datasets and research articles. Each article described how participants were recruited.
Ethics oversight	Ethical approval will not be required because this meta-analysis retrieved and synthesised existing data.

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

Life sciences	\times	Behavioural & social sciences	Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see <u>nature.com/documents/nr-reporting-summary-flat.pdf</u>

Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This meta-analysis examined lab-based techniques in modulating intrusive memories from lab-analogue trauma exposure. All data are quantatitive experimental data, extracted from included research articles.
Research sample	This meta-analysis synthesized data extracted from existing datasets and research articles. Sample characteristics are provided in Table 1. Specific research samples for each study were described in the included research articles.
Sampling strategy	This meta-analysis synthesized data extracted from existing datasets and research articles. Sampling strategies were reported in the included research articles.
Data collection	This meta-analysis synthesized data extracted from existing datasets and research articles. The original data were recorded using computer-based tasks, pen-and-paper, mobile phones.
Timing	This meta-analysis started the first literature search and data input on Dec 15th, 2020, and was updated Dec 12th, 2023.
Data exclusions	This meta-analysis synthesized data extracted from existing datasets and research articles. Article inclusion and exclusion was provided in the Figure 3 PRISMA flowchart.
Non-participation	This meta-analysis synthesized data extracted from existing datasets and research articles. Information on non-participation was provided in the included research articles.
Randomization	This meta-analysis synthesized data extracted from existing datasets and research articles. Information on randomization was provided in the included research articles.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

Materials & experimental systems		Me	/lethods	
n/a	Involved in the study	n/a	Involved in the study	
\boxtimes	Antibodies	\boxtimes	ChIP-seq	
\boxtimes	Eukaryotic cell lines	\ge	Flow cytometry	
\boxtimes	Palaeontology and archaeology	\mathbf{X}	MRI-based neuroimaging	
\boxtimes	Animals and other organisms			
\boxtimes	Clinical data			
\boxtimes	Dual use research of concern			
\boxtimes	Plants			

Plants

Seed stocks	Report on the source of all seed stocks or other plant material used. If applicable, state the seed stock centre and catalogue number. If plant specimens were collected from the field, describe the collection location, date and sampling procedures.
Novel plant genotypes	Describe the methods by which all novel plant genotypes were produced. This includes those generated by transgenic approaches, gene editing, chemical/radiation-based mutagenesis and hybridization. For transgenic lines, describe the transformation method, the number of independent lines analyzed and the generation upon which experiments were performed. For gene-edited lines, describe the editor used, the endogenous sequence targeted for editing, the targeting guide RNA sequence (if applicable) and how the editor
Authentication	was applied. Describe any authentication procedures for each seed stock used or novel genotype generated. Describe any experiments used to assess the effect of a mutation and, where applicable, how potential secondary effects (e.g. second site T-DNA insertions, mosiacism, off-target gene editing) were examined.

nature portfolio | reporting summary