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BRIEF REPORT

Retrieval suppression induced forgetting on 1-week-old consolidated episodic memories

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Abstract

Retrieval suppression has been established to cause forgetting on a wide range of memory types, but mostly in newly formed memories. Over time, the consolidation process stabilizes memory and changes the memory locus in the brain, which may affect the effectiveness of retrieval suppression. In two experiments, we examined whether retrieval suppression can induce forgetting on consolidated episodic memories and explored its potential reliance on explicit memory reactivation or spontaneous memory intrusions to destabilize the consolidated memory. We found that, compared with associative interference, another well-established forgetting approach, retrieval suppression consistently induced forgetting on 1-week-old memories. This suppression-induced forgetting was uncovered stably via an independent retrieval cue, suggesting its effect being on the target memory itself. However, we did not find evidence of modulation on the suppression-induced forgetting by either explicit reactivation or spontaneous intrusions. Together, our results extend the suppression-induced forgetting to episodic memories that have been consolidated for 1 week and suggest that retrieval suppression could destabilize consolidated memories.

Keywords Intrusion · Associative interference · Retrieval suppression · Forgetting · Consolidation · Reconsolidation

Introduction

Unwanted memories, including those associated with traumatic and aversive experiences, are often vivid and long lasting, which pose a significant threat to mental health. To control their influences, people could voluntarily suppress these memories from entering their consciousness (Engen & Anderson, 2018). Effective suppression causes the forgetting of various formats of memories (Anderson & Hulbert, 2021). However, forgetting by voluntary suppression may be rendered difficult by memory consolidation. While memory is fragile and susceptible to disruptions initially, it becomes stabilized over time through consolidation. Consolidation not only stabilizes the memory representations (Dudai, Karni, & Born, 2015; Squire et al., 2015), but also gradually reorganizes the memory locus (Dudai et al., 2015; Frankland & Bontempi, 2005; McGaugh, 2000), which jointly improve the memory's resistance to disruptions. To date, it is unclear how consolidation impacts the effectiveness of retrieval suppression and, importantly, how to deal with the challenges consolidation presents to memory suppression.

Models of memory consolidation have suggested that consolidated memories gradually transform from the hippocampus to neocortical regions (Frankland & Bontempi, 2005; Squire et al., 2015). This process, known as systems consolidation, occurs in a time course that could be in the order of several years. Recent studies have shown measurable changes in memory locus over several hours, indicating the occurrence of systems consolidation in a short time course (Brodt et al., 2018; Takashima et al., 2009). Despite that, possibly due to the rapid decay of episodic memories after the initial acquisition, most laboratory studies, not limited to those on retrieval suppression, have focused on memories formed within hours. One study examining the effect of consolidation on retrieval suppression found that, after a 24-h consolidation, episodic memories became resistant to retrieval suppression and the hippocampal-dependent

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memory representations shift to neocortical representations (Liu et al., 2016). Attempts have also been made to apply retrieval suppression on autobiographical memories formed months or years ago (Noreen & MacLeod, 2014; Stephens et al., 2013). However, in order to provide autobiographical memory materials for experimental manipulations, participants are often required to recollect autobiographical memories before suppression training. Because memory retrieval may introduce new memories, the successful suppression-induced forgetting may be on the new memories formed during retrieval rather than the consolidated autobiographical memories. Therefore, direct evidence is lacking concerning whether retrieval suppression is effective in impairing episodic memories that have been consolidated for a longer time.

Studies on memory reconsolidation have suggested that consolidated memories re-enter an active state after explicit memory reactivation (Lee et al., 2017). As a result, forgetting treatments that are ineffective in disrupting consolidated memories become effective when being implemented upon a brief memory reactivation (Hupbach et al., 2007; Kroes et al., 2014; Monfils et al., 2009; Nader et al., 2000; Zhu et al., 2016). For episodic memories, reactivation initiates neural reinstatements of the consolidated memories, which predict updating of the memory through reconsolidation (Gershman et al., 2013). At the behavioural level, the neural reinstatements may be reflected as spontaneous memory intrusions. It has been suggested that suppression could be retroactively triggered by the occurrence of memory intrusions coupled with the goal of excluding the memory from consciousness (Detre et al., 2013). However, the occurrence of conscious memory intrusions would decline along with the memory stabilization during consolidation, which may diminish the suppression-induced forgetting effect. So far, it is unknown whether retrieval suppression would be benefited from explicit memory reactivation and conscious memory intrusions on consolidated memories.

To test the effectiveness of retrieval suppression on consolidated memories, we applied retrieval suppression to episodic memories that have been consolidated for 1 week (Fig. 1). One advantage of retrieval suppression is that its forgetting effect is on the target memory itself and is thus independent of retrieval cues. To validate such a characteristic, an independent cue that did not receive direct retrieval suppression or associative interference was used to retrieve the target memory in the memory test in addition to the trained cues. Meanwhile, because the independent cue was not presented during forgetting training, it has been suggested to provide a clean measure of the forgetting effect (Anderson & Green, 2001; Zhu et al., 2016; Zhu et al., 2019). As a comparison to retrieval suppression, we included another widely used forgetting approach – associative interference. On the one hand, while associative interference disrupts newly formed episodic memories, it often fails to work on consolidated memories (Chan & LaPaglia, 2013; Hupbach et al., 2007; Zhu et al., 2016). On the other hand, associative interference does not employ an inhibition mechanism as retrieval suppression (Anderson, 2003; Wang et al., 2015). The inclusion of associative interference thus serves as a control for forgetting through inhibitory control.

Experiment 1

To assist forgetting, an explicit memory reactivation procedure that has been shown to destabilize consolidated memories (Elsey et al., 2018) was included in Experiment 1. Participants reported the occurrence of early memory intrusions at the beginning of suppression or interference training in Experiment 1a. To avoid the influence of intrusion reporting,

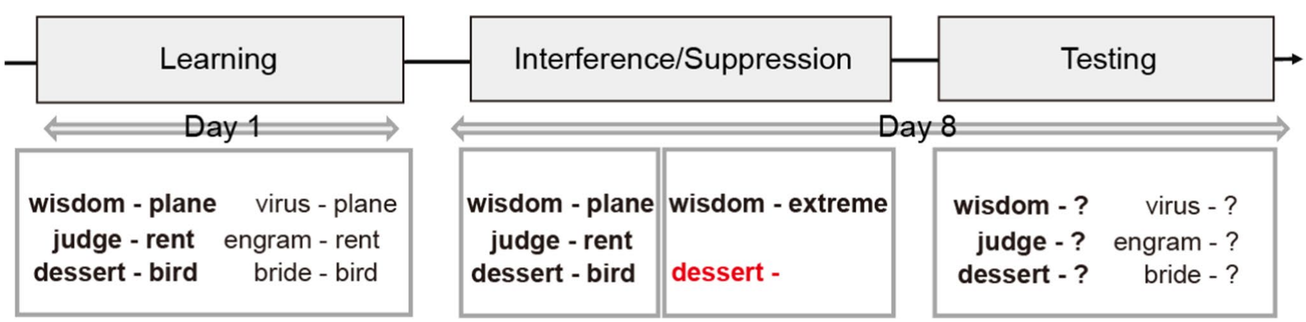

Fig. 1 Experimental procedure. (**Top**) The experiment was composed of three phases: Learning, Interference/Suppression, and Testing. (**Bottom**) Participants studied double-cue/one-target word pairs in the form of A-X/B-X on Day 1. One week later, on Day 8, A-X pairs were first reactivated (only in Experiment 1), and then received associative Interference and retrieval Suppression. Interference was done by pairing the trained cue with a substitute word for relearning (black font); Suppression was done by participants suppressing the retrieval of the target word (red font). Interference/Suppression was repeated 12 times on each trained item. Finally, a cued-recall test was given on all pairs by using either cue A or cue B words. For illustration purposes, associates in the trained-cue group (i.e., A-X pairs) were shown in bold font and associates in the independent-cue group (i.e., B-X pairs) were shown in regular font

the subjective intrusion rating procedure was removed in Experiment 1b.

Method

Participants

Thirty-six (aged 19–28 years, 21 females) and 31 (aged 19–31 years, 24 females) healthy college students were recruited in Experiments 1a and 1b; two participants dropped out during Experiment 1a. The sample size for the present experiments was determined based on a priori power analysis of our previous studies using similar materials and procedures (Wang et al., 2015, 2019; Zhu et al., 2016), which indicated that a sample of 31–34 participants would be sufficient to observe suppression-induced forgetting in a paired comparison (with a two-sided $\alpha = 0.05$, power = 0.85). All participants had normal reading and comprehension abilities and had no known neurological disorders. Participants gave written informed consent in accordance with the procedures and protocols approved by the human participant review committee of Peking University. Two participants failed to report memory intrusions due to technique issues in Experiment 1a. Thus the intrusion data were collected from 32 participants. The data are available via the Open Science Framework and can be accessed at https://osf.io/tz2kq/.

Materials

Experiments 1a and 1b used the same stimuli. The stimuli contained 60 double-cue/one-target word pairs. Each pair was made up of two two-character Chinese words (e.g., "wisdom – plane"). A double-cue/one-target design (Zhu et al., 2016, 2019; Zhu & Wang, 2021) was used, which paired each target separately with two different cues (e.g., "wisdom – plane" and "virus – plane"). Therefore, two series of word pairs, each consisting of 30 word pairs, existed in the form of A-X and B-X. Both A-X and B-X pairs were studied, but only the A-X pairs received Interference/Suppression training. The 30 A-X pairs were divided into three groups (10 pairs per group), which were to be used in one of three conditions: Interference, Suppression, and Control. The 30 B-X pairs were divided into the same three groups according to their matched A-X pairs. Ten novel words were used as substitutes for interference training, in which each substitute word was paired with one cue A word to interfere with the original A-X association (e.g., learning "wisdom – extreme" to interfere with "wisdom – plane"). The arrangement of experimental conditions for the three groups was counterbalanced across participants. Care was taken to avoid pre-existing semantic relationships between items from different pairs.

Procedure

Both experiments consisted of three phases: Learning, Interference/Suppression, and Testing.

Learning phase Participants studied two series of 30 cue-target word pairs (i.e., 30 A-X and 30 B-X pairs). All pairs were first presented on the screen sequentially, each for 3 s, interleaved by a fixation cross for 1 s. To assist learning, a test-feedback session was given afterward (Zhu et al., 2016), in which each cue was presented for up to 3 s during which participants recalled the response word and reported whether they could recall the target word or not by key pressing. Upon key pressing or when the time window expired, the target word was shown on the screen for 1 s. Participants were instructed to use the feedback to increase their knowledge of the pairs. At the end of each session, participants completed a 5-min arithmetic task and were then tested on all 60 pairs in a cued-recall test without feedback. The test-feedback cycles continued until all the pairs were correctly recalled in the cued-recall test. The order of items in the learning, test-feedback, and cued-recall test phases was each determined by a custom randomization script in MATLAB (The MathWorks Inc., Natick, MA, USA).

Interference/Suppression phase Interference and Suppression training were given 7 days later, on A-X pairs. Accordingly, cue As were called the Trained cues, while cue Bs, which shared the same targets with cue As but did not receive any Interference/Suppression training, were called the Independent cues. Explicit memory reactivation was given at the beginning, during which all A-X pairs were presented to participants sequentially, each for 2 s, and participants passively looked at the pairs without doing specific tasks. Interference and Suppression training followed. For Interference (hereafter, R-Interference, representing the abbreviation for Reactivation-Interference) trials, cues from one subset of the A-X pairs were each presented along with a substitute word for relearning. Participants were asked to study and memorize the new word pairs. For Suppression (hereafter, R-Suppression) trials, cues from another A-X subset were presented alone on the screen with no target word alongside. A direct-suppression instruction was used. Participants were asked to avoid thinking about the associated target word while directing their attention to the cue word (Wang et al., 2019). To help participants discriminate the two conditions, cues for retrieval suppression were presented in red font while cues for associative interference were presented in black font (Fig. 1). Cues from the remaining A-X subset were not shown during this phase and served as the control for the trained-cue group. Each trial lasted 4 s, and each Interference/Suppression training was repeated 12 times across six blocks. Trials from different conditions were presented in a pseudorandom order such that the mean ranks of items from different conditions were matched.

In the first R-Interference/R-Suppression trial of each pair in Experiment 1a, participants were instructed to report the occurrence of spontaneous memory intrusions. Specifically, they reported whether the target word came to mind at the end of the trial by key pressing. The memory intrusion in the first trial was supposed to reflect the spontaneously generated intrusions of the consolidated memory upon encountering its associated cues. Memory intrusions in the following repetitions were not collected to avoid the confounding effect of Interference/Suppression-induced forgetting, which would reduce memory intrusions due to the weakened memory strengths (Gagnepain et al., 2017). Trials with intrusions were labelled as positive trials, and the percentage of positive trials was calculated for each condition.

Testing phase A recall test was given 5 min later on all 60 pairs on the 1-week-old A-X and B-X word pairs. Each cue word was presented on the screen sequentially. Participants typed the corresponding target words originally paired in the learning phase into the computer in a self-paced manner. Words from different conditions were presented in a pseudorandom order such that the mean positions of items from different conditions were matched. Memory for the substitute learning in the R-Interference condition was not-tested.

Results

Reactivation-coupled interference and suppression-induced forgetting of 1-week-old memories

The percentage of memory recalled in the final recall test was calculated in each condition. We performed a 2 (cue types: trained cue and independent cue) × 3 (forgetting treatments: R-Interference, R-Suppression, and Control) repeated-measures ANOVA on the recall accuracies in Experiments 1a and 1b, respectively.

Experiment 1a The interaction effect between the two factors was not significant (Fig. 2a; $F(2,66) = 1.80$, $p = .173$, $\eta_p^2 = 0.05$), suggesting similar effects from the two forgetting approaches. Considering that the trained and independent cues received different manipulations, we examined the memory impairment under each cue type separately. We found that the main effect of the forgetting treatment was significant in the trained-cue condition ($F(2,66) = 3.68$, $p = .031$, $\eta_p^2 = 0.10$). Specifically, associative interference after a brief reactivation (R-Interference) caused a significant memory impairment in the trained-cue group ($t(33) = -2.64$, $p = .013$, Cohen's $d = 0.45$). Reactivation-coupled retrieval suppression (R-Suppression) decreased memory performance numerically but not significantly ($t(33) = -1.14$, $p = .262$, Cohen's $d = 0.19$). The independent-cue condition also showed a significant main effect across the forgetting treatments ($F(2,66) = 7.86$, $p < .001$, $\eta_p^2 = 0.19$). Both R-Interference ($t(33) = -3.23$, $p = .003$, Cohen's $d = 0.55$) and R-Suppression ($t(33) = -3.28$, $p = .002$, Cohen's $d = 0.56$) caused a significant memory impairment when compared with the control condition. The forgetting effects did not differ between R-Interference and R-Suppression ($t(33) = 0.72$, $p = .475$, Cohen's $d = 0.12$).

Experiment 1b The interaction effect between the two factors was not significant (Fig. 2b; $F(2,60) = 1.05$, $p = .355$, $\eta_p^2 = 0.03$) either. As in Experiment 1a, we examined the memory impairment under each cue type separately. The main effect of the forgetting treatment was significant in the trained-cue condition ($F(2,60) = 3.58$, $p = .034$, $\eta_p^2 = 0.11$).

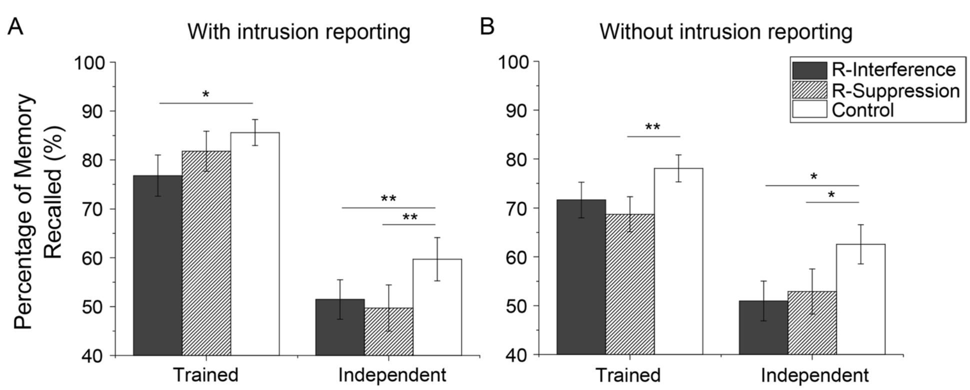

Fig. 2 Results for Experiment 1. **a** Percentage of memory recalled in Experiment 1a. R-Interference caused significant memory impairment in both the trained- and independent-cue groups. R-Suppression caused memory impairment in the independent-cue group. **b** Percentage of memory recalled in Experiment 1b. R-Interference caused significant memory impairment in the independent-cue group. R-Suppression caused memory impairment in both the trained- and independent-cue groups. * $p < .05$, ** $p < .01$ (two-tailed t-test); error bars indicate SEM

Specifically, R-Suppression caused a significant memory impairment in the trained-cue group (t(30) = -2.77, p = .010, Cohen's d = 0.50). R-Interference decreased memory performance numerically but not significantly (t(30) = -1.80, p = .082, Cohen's d = 0.32). The independent-cue condition also showed a significant main effect across the forgetting treatments (F(2,60) = 5.22, p =.008, $\eta_p^2 = 0.15$). Both R-Interference (t(30) = -2.70, p = .011, Cohen's d = 0.48) and R-Suppression (t(30) = -2.64, p = .013, Cohen's d = 0.47) reduced memory performance relative to the control condition. The forgetting effects did not differ between R-Interference and R-Suppression (t(30) = 0.54, p = .589, Cohen's d = 0.10). Therefore, both R-Interference and R-Suppression impaired 1-week-old episodic memories, and their effects were similar, as illustrated by the independent cue.

Forgetting was not predicted by the degree of initial memory intrusions

We examined the association between the degree of early memory intrusions, which has been suggested to trigger retroactive suppression (Benoit et al., 2015; Levy & Anderson, 2012), and the forgetting of consolidated memories. We performed a Pearson correlation analysis between the percentage of memory intrusions and the recall accuracy under each manipulation in the independent-cue condition. No significant correlation was found in either R-Interference (Fig. 3a; r(32) = 0.15, p =.422) or R-Suppression (Fig. 3b; r(32) = -0.00, p = .990). Instead, a marginally significant correlation was found between the averaged intrusions of the two experimental conditions and the memory performance in the control condition (Fig. 3c, r(32) = 0.34, p = .055), possibly suggesting that participants having a better baseline memory tended to experience more memory intrusions.

Independent-cue retrieval was free of influence by intrusion rating

Considering that subjective intrusion rating may increase the chance of memory intrusions and thus influence the memory performance, we performed a 2 (cue types) × 3 (forgetting treatments) × 2 (experiments: Experiment 1a and Experiment 1b) across-experiment repeated-measures ANOVA examining whether the memory performance differed across experiments. Neither the interaction effect of the three factors (F(2,126) = 2.13, p = .123, $\eta_p^2 = 0.03$) nor the main effect of experiments (F(1,63) = 0.60, p =.440, $\eta_p^2 = 0.01$) was significant. However, we observed that the interaction effect between the cue types and the experiments was significant (F(1,63) = 4.93, p = .030, $\eta_p^2 = 0.07$). We then performed a 3 (forgetting treatments) × 2 (experiments) repeated-measures ANOVA under each cue type. We found a significant main effect of experiments on the memory performance under trained- (F(1,63) = 4.17, p = .045, η_p^2 = 0.06) but not under independent-cue (F(1,63) = 0.11, p = .739, $\eta_p^2 = 0.002$) retrieval. Therefore, the memory performance in the independent-cue condition was not influenced by subjective intrusion rating. The forgetting effect under the independent-cue retrieval (Fig. 2a and b) provided evidence that R-Interference and R-Suppression disrupted 1-week-old episodic memories.

Experiment 2

Because the explicit memory reactivation procedure in Experiment 1 offered an opportunity for relearning, one could argue that the forgetting effect was not in the 1-week-old memory but reflected disruptions of the enhanced memory component formed on Day 8. To exclude this possibility, Experiment 2 removed the explicit memory reactivation

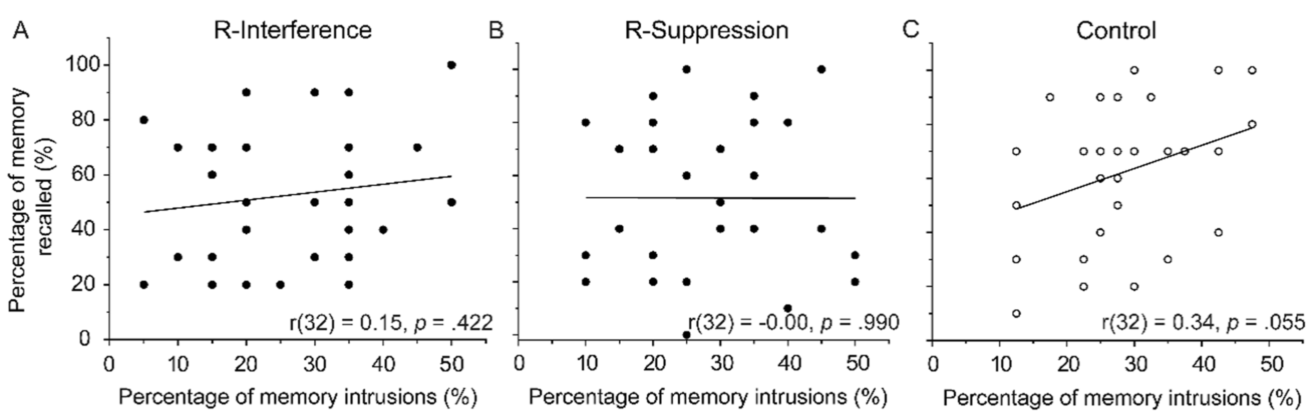

Fig. 3 Correlation between memory intrusions and memory performance. The percentage of memory intrusions did not predict the percentage of memory recalled in the R-Interference (**a**) or R-Suppression (**b**) condition. **c** The percentage of memory intrusions marginally significantly predicted the percentage of memory recalled in the Control condition

procedure and applied associative Interference and retrieval Suppression directly on the consolidated memories on Day 8.

Method

Participants and materials

Thirty-five (aged 19–32 years, 29 females) native Chinese speakers were recruited, and three dropped out during the experiment. The remaining 32 participants had normal reading and comprehension abilities and had no known neurological disorders. Participants gave written, informed consent in accordance with the procedures and protocols approved by the human participant review committee of Peking University. The same materials were used as in Experiment 1.

Procedure

The procedure was the same as in Experiment 1, except that no explicit reactivation was given. Namely, participants received Interference and Suppression training on two groups of A-X pairs on Day 8 directly.

Results

Retrieval suppression without explicit reactivation impaired 1-week-old episodic memories

A 2 (cue types: trained cue and independent cue) × 3 (forgetting treatments: Interference, Suppression, and Control) repeated-measures ANOVA on the recall accuracy showed a significant interaction effect between the two factors (Fig. 4a; F(2, 62) = 5.70, p =.005, η_p^2 = 0.16), suggesting a different pattern in the Interference and Suppression manipulations. We found that, when without explicit reactivations, Interference did not cause any forgetting in either the trained- (t(31) = -0.81, p = .427, Cohen's d = 0.14) or independent-cue (t(31) = -1.26, p = .217, Cohen's d = 0.22) group. In contrast, Suppression successfully impaired the memory performance in the independent-cue group (t(32) = -4.45, p < .001, Cohen's d = 0.79), although not in the trained-cue group (t(31) = 0.13, p = .902, Cohen's d = 0.02). Therefore, while consolidated memories are resistant to associative interference, they are susceptible to disruptions by retrieval suppression.

Suppression-induced forgetting was not predicted by initial memory intrusions

To examine whether intrusions would trigger forgetting on consolidated memories, we explored the association between intrusion and memory performance. First, we performed a cross-subject correlation analysis between the memory intrusions and memory performance in each condition and found no significant correlations (Fig. 4c; Interference: r(32) = -0.19, p = .291; Suppression: r(32) = -0.02, p = .910; Control: r(32) = 0.32, p = .076). Next, we performed a within-subject analysis where the recall performance for the Suppression pairs that had intrusions versus those did not were compared (Fig. 4b). A 2 (forgetting treatments: Interference and Suppression) × 2 (intrusion states: with intrusion and no intrusion) repeated-measures ANOVA on the percentage of items recalled found no interaction effect (F(1, 31) = 1.10, p =.303, η_p^2 = 0.03). Despite that, we explored the simple effect in each condition. We found that the memory performance was marginally significantly better for pairs with intrusion than pairs without intrusion in the Interference condition (t(31) = 1.43, p = .082, one-tailed, Cohen's d = 0.25), but no differences were found in the Suppression condition (t(31) = 0.30, p = .384, one-tailed, Cohen's d = 0.05). In all cases, intrusions did not facilitate forgetting.

Explicit reactivation or not did not affect the forgetting effect

So far, we observed stable suppression-induced forgetting in the independent-cue group regardless of whether explicit reactivation was applied or not. To explore whether explicit reactivation contributed to the forgetting effect, we performed a 2 (cue types) × 3 (forgetting treatments) × 2 (experiments: Experiment 1a vs. Experiment 2) repeated-measures ANOVA examining whether the memory performance was modulated by the reactivation manipulation. We found no interaction effect (F(2, 128) = 1.15, p =.319, η_p^2 = 0.02). Considering that the forgetting effect was stably observed only in the independent-cue condition, we performed a 3 (forgetting treatments) × 2 (experiments) repeated-measures ANOVA on the memory performance in the independent-cue condition. No interaction effect was observed either (F(2, 128) = 1.67, p = .193, η_p^2 = 0.03). Finally, we directly examined whether associative interference and retrieval suppression showed different forgetting patterns in the two experiments. A 2 (forgetting treatments: associative interference vs. retrieval suppression) × 2 (experiments) repeated-measures ANOVA on the forgetting effect in the independent-cue group showed a significant interaction effect between the two factors (F(1, 64) = 4.09, p = .047, η_p^2 = 0.06). However, when the degree of memory intrusions was included as a covariate, the interaction effect disappeared (F(1, 60) = 1.67, p = .201, η_p^2 = 0.03). Therefore, we did not find evidence that suppression- or interference-induced forgetting is benefited by explicit memory reactivation.

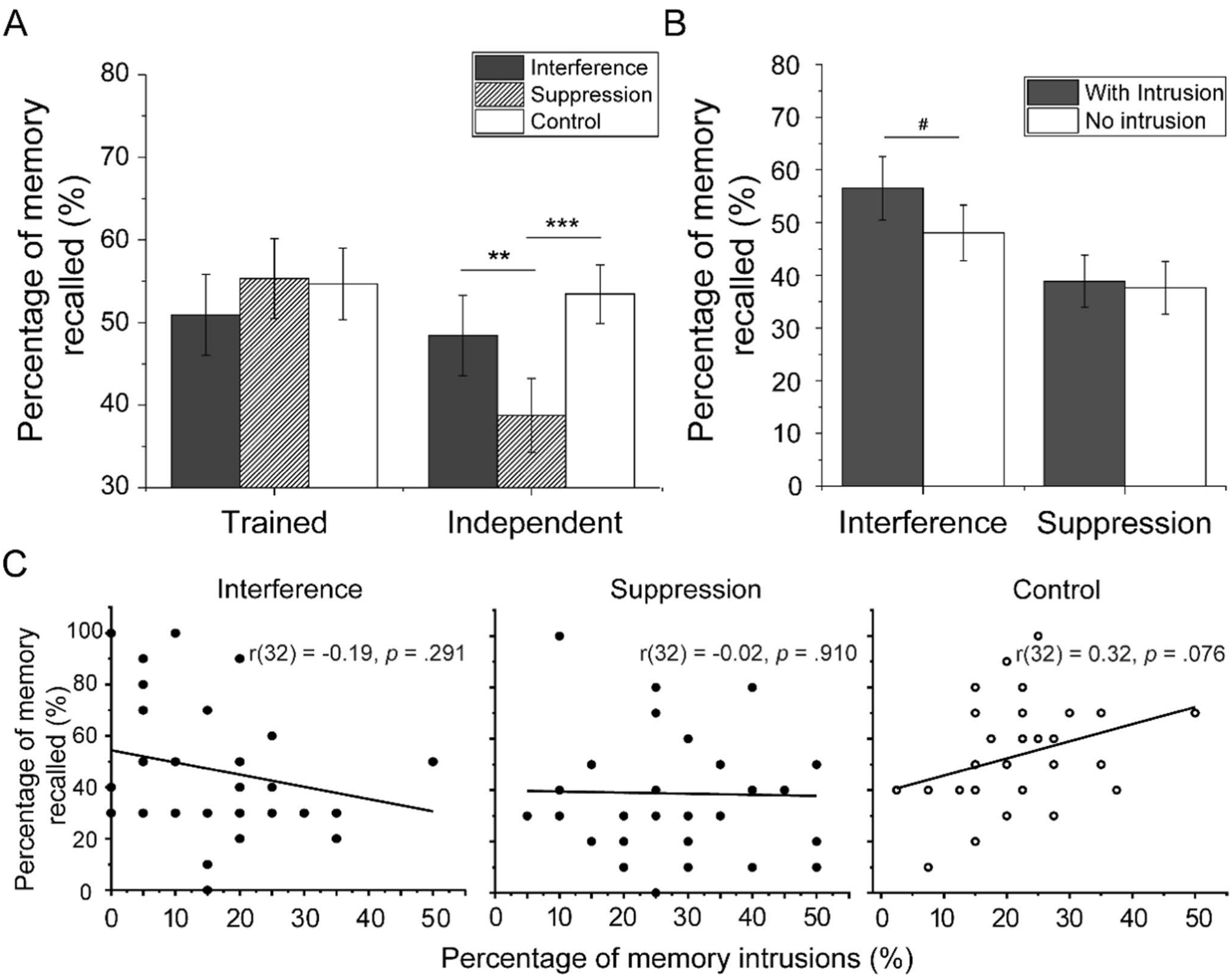

Fig. 4 Results for Experiment 2. **a** Retrieval suppression caused significant impairment in consolidated memory as revealed by the independent-cue retrieval. **b** Items that intruded during retrieval suppression showed a trend for better memory in the Interference condition. # $p < .09$ (one-tailed t-test); ** $p < .01$, *** $p < .001$ (two-tailed t-test); error bars indicate SEM. **c** Correlation between the percentage of memory intrusions and the memory performance in each condition under independent-cue retrieval

Discussion

The current study extended the suppression-induced forgetting effect to episodic memories that have been consolidated for 1 week. By comparing the effect of retrieval suppression with that of associative interference, we showed that only retrieval suppression consistently disrupted 1-week-old memories. We did not find evidence that the suppression-induced forgetting effect was modulated by explicit memory reactivation or spontaneous memory intrusions. Therefore, retrieval suppression itself is able to destabilize consolidated episodic memories.

Our result is complementary to previous findings of suppression-induced forgetting in autobiographical memory (Noreen & MacLeod, 2014; Stephens et al., 2013). Autobiographical memories provide a natural source for studies on consolidated episodic memories. However, in laboratory studies, participants' memories are often retrieved and labeled before the application of forgetting manipulations. Findings from such procedure are criticized because forgetting may occur to the freshly retrieved and enhanced memory components rather than the original consolidated memory components. Likewise, in Experiment 1, explicit memory reactivation enhanced the consolidated memory, and the retrieval suppression may only work to disrupt the enhanced memory component. By removing the explicit reactivation procedure, Experiment 2 avoids this problem. Notably, comparison between the two experiments suggested that the explicit reactivation did not influence memory performance in the independent-cue condition. Our finding is also consistent with the findings that people with higher suppression ability in daily life suffer less from the influence of aversive experiences that could have happened a long time ago (Hulbert & Anderson, 2018; Mary et al., 2020; Streb et al., 2016).

Retrieval suppression is suggested to be achieved through inhibitory control initiated by the prefrontal cortex onto the hippocampus, which is widely revealed in the suppression of newly-formed memories (Anderson et al., 2004; Anderson & Hanslmayr, 2014). However, across time, consolidated memories become more independent of the hippocampus and gradually transform to neocortical regions (Squire et al., 2015). Therefore, retrieval suppression on consolidated memories may adopt a different pathway than the prefrontal-hippocampus pathway. In line with this, Liu et al. (2016) has found that retrieval suppression on 24-h-old memories involves more prefrontal engagement and less hippocampal disengagement. However, while rapid changes could happen with a 24-h overnight consolidation (Du et al., 2019; Liu et al., 2016; Ritchey et al., 2015), the systems consolidation would induce more changes across days, weeks, and longer periods (Bonnici et al., 2012, 2013; Takashima et al., 2006). For instance, 1-week-old memory differs from 1-day-old memory in its reliance on the hippocampus and para-hippocampal cortex (Du et al., 2019). Mechanistically, the finding of suppression-induced forgetting on consolidated memories suggests that the inhibitory control pathway is not restricted to the hippocampus but extends to neocortical regions. Future studies should extend the effect to a time course of several weeks or months.

Our finding that retrieval suppression effectively disrupts 1-week-old episodic memories contrasts with the previous study by Liu et al. (2016), which did not find suppression-induced forgetting in 24-h-old memories. The current study differed from Liu et al.'s (2016) study in two important aspects. First, the forgetting effect in the current study was revealed by an independent cue, which shared the associated target with the trained cue but was not presented during retrieval suppression or associative interference. Direct presentation of the trained cue has been found to enhance the memory for the associations, which often masks the forgetting effect on the target memory (Zhu et al., 2016; Zhu & Wang, 2021). The present study further showed that explicit reactivation and subjective intrusion rating also enhanced memory for the trained-cue group. Unlike the trained-cue retrieval, the independent-cue retrieval tests the strength of memory itself. This explains the null effect under the trained-cue retrieval in the current study and in Liu et al. (2016). Using the double-cue procedure, Wang et al. (2021) have reported suppression-induced forgetting of 24-h-old conditioned threat memories. Second, Experiments 1a and 2 included a procedure asking participants to report intrusions of consolidated memories. This procedure may, in turn, increase the chance of memory intrusions, which then increases the degree of suppression-induced forgetting.

The suppression-induced forgetting in 1-week-old episodic memories was not associated with the degree of memory intrusions. This might be due to conscious memory intrusions being limited after consolidation. For instance, items that were forgotten due to natural decay would not trigger conscious intrusions and thus complicated the association between forgetting and conscious intrusion. In fact, the association between memory intrusions and suppression-induced forgetting is nonlinear. Computational modelling and neural science evidence showed that only moderate levels of activation of the to-be-suppressed item led to diminished performance on the final memory test (Detre et al., 2013; Ritvo et al., 2019). Previous studies have shown that explicit reactivation, which increases memory intrusions, may strengthen and stabilize the memory trace and hinder memory disruptions (Amar-Halpert et al., 2017; Zhu et al., 2016). On the other hand, the reconsolidation theory also has suggested that consolidated memories re-enter an unstable state and become susceptible to modifications upon reactivation (Elsey et al., 2018; Lee et al., 2017). Future studies should explore whether the current forgetting effect recruits the neural circuit of reconsolidation disruptions and whether it will be facilitated by a moderate level of memory intrusions.

Interleaving associative interference trials with retrieval suppression trials may have led participants to recruit suppression in associative interference trials. The associative interference manipulation here is similar to the thought substitute method, which recruits an inhibitory control mechanism to resolve the competition between retrieving the original memory and learning the alternative associate (Benoit & Anderson, 2012). This explains the cue-independent forgetting, which is a characteristic of forgetting by suppression, in the associative interference condition. Notably, the present study did not examine the strength of the interference memory and could not ensure that the null effect in Experiment 2 was due to low interference strength. Future studies should examine associative interference as well as thought substitution on consolidated memories.

In conclusion, we provide consistent evidence that retrieval suppression induces forgetting on 1-week-old episodic memories. Our findings also suggest that, even without the assistance of explicit memory reactivation or conscious memory intrusions, retrieval suppression is able to destabilize consolidated memories. Retrieval suppression may be able to disrupt consolidated memories.

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Author's contribution Both authors designed the study. Z. Zhu carried out the experiments. Y. Wang analyzed the data. Y. Wang and Z. Zhu wrote the manuscript. Both authors discussed the results and contributed to the final manuscript.

Declaration

Competing interests The authors declare no competing financial interests.

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Open practices statement The data are available via the Open Science Framework and can be accessed at https://osf.io/tz2kq/. The materials of this study are available from the authors upon reasonable request. The experiment reported in this study was not preregistered.