AMERICAN PSYCHOLOGICAL ASSOCIATION
Journal of Experimental Psychology: General

ISSN: 0096-3445

2021, Vol. 150, No. 3, 401–413
http://dx.doi.org/10.1037/xge0000782

Forgetting Unrelated Episodic Memories Through Suppression-Induced Amnesia

Zijian Zhu
Shaanxi Normal University

Yingying Wang
Peking University

Cognitively suppressing the retrieval of an unwanted memory causes its forgetting and, in the meantime, disrupts hippocampal functions. The present study investigated whether retrieval suppression induces virtual amnesia, which disturbs any existing memories that are reactivated in the temporal vicinity but are otherwise unrelated to the targets of suppression. Participants performed retrieval suppression on a set of memories while cues of an unrelated set of memories were briefly presented near in time to the suppression trials. Results showed that retrieval suppression impaired the retrieval of both the directly suppressed content and the reactivated unrelated memory. This amnesic shadow functioned in both the forward and backward temporal directions, and its forgetting effect was revealed by independent cues that were not presented in the shadow. Remarkably, a negative memory could be impaired simply by presenting it between the suppression episodes of an unrelated neutral memory. These findings provide support for systemic influence of retrieval suppression on hippocampal functions and offer a way to disrupt existing episodic memory strategically.

Keywords: retrieval suppression, TNT paradigm, amnesic shadow, forgetting, independent cue

Supplemental materials: http://dx.doi.org/10.1037/xge0000782.supp

Following a traumatic experience, memories of the event often intrude. To deal with this, people often try to exclude the unwanted memory from awareness. Such attempts not only protect people from being hurt by the ongoing intrusions but also diminish the memory in the long run (Anderson & Hanslmayr, 2014; Depue, Banich, & Curran, 2006; Gagnepain, Henson, & Anderson, 2014). Research on motivated forgetting indicates that this process, known as retrieval suppression, is mediated by the downregulation of hippocampal activity (Anderson et al., 2004; Benoit & Anderson, 2012; Gagnepain, Hulbert, & Anderson, 2017) and is related to a higher concentration of inhibitory neurotransmitters in the hippocampus in the resting state (Schmitz, Correia, Ferreira, Prescot, & Anderson, 2017). Recent research found that this downregulation causes a "virtual lesion'" on the hippocampus, which disrupts the encoding of new unrelated experiences occurring near in time to retrieval suppression efforts (Hulbert, Henson, & Anderson, 2016; Hulbert, Hirschstein, Brontë, & Broughton, 2018). Such systemic influence on hippocampus-dependent processes mimics the effect of hippocampal amnesia and is referred to as the amnesic shadow. In this sense, it should be possible to forget any hippocampally dependent memories merely by exposing it to the amnesic shadow.

Here, we further hypothesized that the amnesic shadow not only influences the encoding of novel information but also is capable of influencing memories that have been encoded into the hippocampus. To test this hypothesis, the present study measured the influence of retrieval or suppression on the later accessibility of previously acquired memories that happened to be cued in the temporal vicinity but were otherwise unrelated to the targets of suppression. To induce retrieval suppression, we used an adapted think/no-think (TNT) procedure (Anderson & Green, 2001). In the TNT procedure, people were presented with a reminder of a past event and cued either to retrieve the associated memory (think trials) or to suppress its retrieval (no-think trials). At the behavioral level, the target item that has been suppressed is impaired in memory (Anderson & Green, 2001), as well as in its affective (Gagnepain et al., 2017), perceptual (Gagnepain et al., 2014; Kim & Yi, 2013), and conceptual (Wang, Luppi, Fawcett, & Anderson, 2019) representations. Recently, Hulbert and colleagues (2016) modified the TNT procedure to a hippocampal modulation (HM) paradigm by inno-

This article was published Online First August 13, 2020.

Zijian Zhu, School of Psychology, Shaanxi Normal University; Yingying Wang, Academy for Advanced Interdisciplinary Studies, Peking University.

This work was supported by the National Natural Science Foundation of China (31421003) and a China Postdoctoral Science Foundation Grant (2019M663621). Zijian Zhu and Yingying Wang developed the study concept and contributed to the study design together. Zijian Zhu performed the programming and data collection. Yingying Wang performed the data analysis. Both authors wrote the article and approved the final version of the manuscript for submission. The authors declare no competing financial interests. The experiments in this article were not formally preregistered. The data are posted on the Open Science Framework at https://osf.io/gxbfc/.

Correspondence concerning this article should be addressed to Zijian Zhu, School of Psychology, Shaanxi Normal University, 199 Changannan Road, Xi'an 710062, China, or to Yingying Wang, Academy for Advanced Interdisciplinary Studies, Peking University, 5 Yiheyuan Road, Beijing 100871, China. E-mail: zhuzijian0203@snnu.edu.cn or yyingwang@pku.edu.cn

vatively inserting innocent bystanders, fresh information that had never been studied, between think or no-think trials. Their findings that retrieval suppression disrupted memory of innocent bystanders presented near in time to suppression provided the first evidence that retrieval suppression induces an amnesic shadow that harms the encoding function of the hippocampus.

In the present study, we adapted the HM paradigm to explore the amnesic shadow effect on an unrelated existing memory. We trained participants to initiate retrieval suppression on a set of memories using the TNT task (Anderson & Green, 2001). Different from Hulbert et al. (2016), innocent bystanders embedded between think or no-think trials were cues of a different and unrelated set of existing memories. The bystander cues were presented to the participants to reactivate the unrelated memory in order to engage the hippocampus. Buffer trials were inserted before and after bystanders to ensure that the same task always preceded/followed bystanders. Unbeknownst to participants, targets for the bystanders would be tested after the TNT phase. Critically, we employed a double-cue/one-target procedure for the bystander memories (Zhu et al., 2016; Zhu, Wang, Jia, & Wu, 2019). That is, the target memory of each bystander cue was tested with both the bystander cue and an independent cue, the latter of which was not presented in amnesic shadow and thus provided a cleaner measure of target memory change. Considering that the amnesic shadow effect is specific to hippocampally dependent memory processes (Hulbert et al., 2016; Hulbert et al., 2018), we used a cued-recall task with both trained and independent cues to test the memory changes on the bystander memories.

We predicted that retrieval suppression would impair an unrelated episodic memory once it was reactivated within its amnesic shadow. Due to the nature of retrieval suppression, some characteristics about the shadow effect were expected. First, retrieval suppression would work on the to-be-suppressed memory rather than particular cue-target associations (Anderson & Green, 2001; Wang, Cao, Zhu, Cai, & Wu, 2015); thus, disruptions on the bystander target should be on the target item itself and persist when retrieved by independent cues. Second, because the amnesic shadow occurs due to inhibited hippocampal activity by retrieval suppression (Hulbert et al., 2016), the degree of shadow-induced forgetting should be predicted by the degree of suppression-induced forgetting. Third, although emotional memories might rely on some different brain regions than neutral memories, due to their common reliance on the hippocampus (Phelps, 2004), the amnesic shadow induced by the suppression of a neutral memory might be able to disrupt an unrelated emotional memory. Here, we provided evidence for the above predictions and confirmed that the amnesic shadow could be exploited to disrupt existing memory. This mechanism provides a way to treat unwanted episodic memories without the need to directly suppress them.

Experiment 1: Reduction in Episodic Memories Due to Amnesic Shadow

We first tested whether retrieval suppression could influence the retrieval performance of an unrelated memory that was reactivated close in time to retrieval suppression. We used the classical TNT paradigm for retrieval suppression (Anderson et al., 2004) and inserted bystander cues of an unrelated memory between two TNT trials. Influence on the bystander memory was examined with cues that were presented during retrieval suppression (trained cues) and with cues that were independent of reactivation or retrieval suppression (independent cues).

Method

Participants. Thirty native Chinese speakers (age range 17–21 years, 11 male) participated in exchange for monetary compensation. No statistical methods were used to predetermine sample size for Experiment 1, but our sample size was chosen to be similar to those reported in previous publications from the lab and in the literature that focused on suppression-induced forgetting (e.g., Gagnepain et al., 2017). All participants had normal or corrected-to-normal vision. They had no reported history of head injury, neurological disease, or learning disability and no red/green color-blindness. Participants provided written consent before participation. Experimental procedures were reviewed and approved by the Human Subject Review Committee of the Shaanxi Normal University.

Materials. The stimuli for the main experiment contained 30 critical TNT pairs and 30 bystander pairs. The nature of the TNT pairs followed previous work (Zhu et al., 2016). The constituent members of each TNT pair were two 2-character Chinese words (e.g., "PORT-SURFACE") that were emotionally neutral and semantically unassociated with each other. A special design of double-cue/one-target was used for bystander pairs (Wang et al., 2015; Zhu et al., 2016; Zhu et al., 2019). That is, each target picture was paired with two different cue words, which formed two series of bystander pairs, in the form of A-X and B-X. The two series were studied and trained separately during the experiment. Critically, cues from one series would be embedded between TNT trials (trained cues), while cues from the other series would not appear in the TNT phase (independent cues). The three members of each bystander pair were emotionally neutral and semantically unassociated with each other. Items from different TNT pairs were also semantically unassociated with items from the bystander pairs.

Critical TNT pairs were divided into three subsets (10/group). For each participant, cues from one subset would appear in the think task, cues from a second subset would appear in the no-think task, and cues from the remaining subset did not reappear during the TNT phase and served as the control group. Critical bystanders were also divided into three subsets (10/group): One subset would be presented between two think trials, one subset would be presented between two no-think trials, and the remaining subset would not appear during the TNT phase (served as the baseline). Each group of bystanders was always used for a fixed group of TNT pairs. The arrangement of experimental conditions for the three TNT (along with its bystander) groups was counterbalanced across participants.

Procedure. The modified HM paradigm consisted of three phases: the study phase, the TNT phase, and the test phase. The procedure is shown in Figure 1.

Study phase. Participants studied three series of cue-target pairs, including two bystander pair series and one TNT pair series. The three series were always studied in a fixed order: first the trained-cue bystander pairs, then the independent-cue bystander pairs, and finally the TNT pairs. This arrangement ensures comparative memory strength of pairs within the same series and avoids memory integration of pairs across different series.

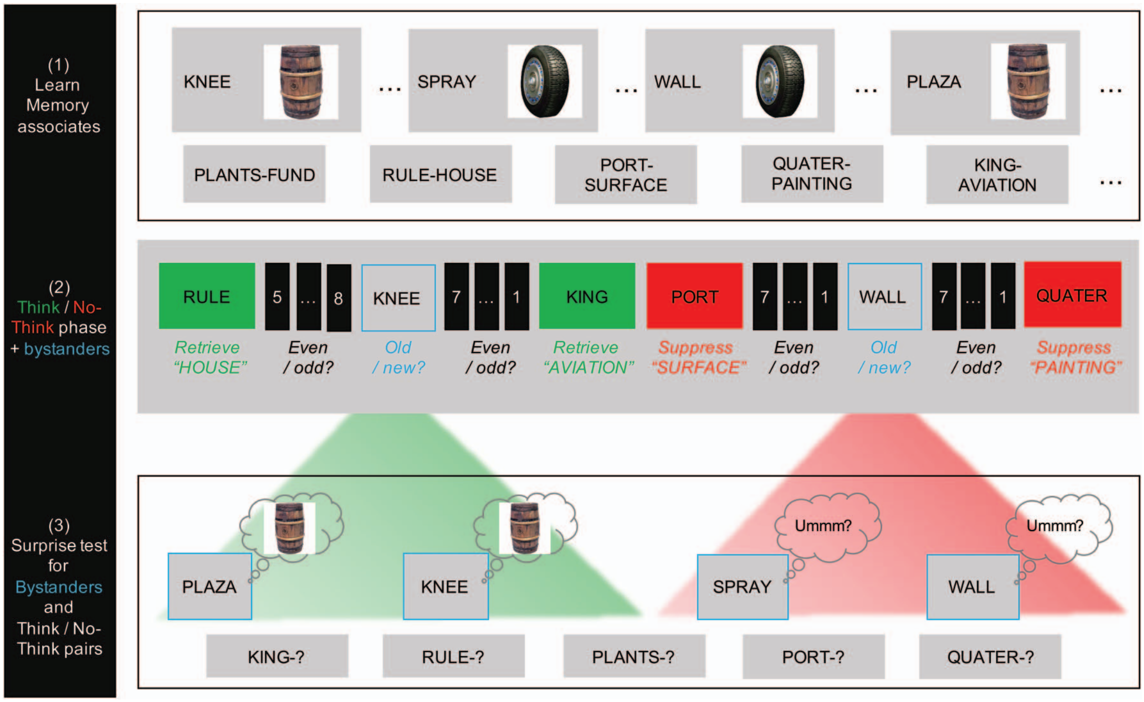

Figure 1. The paradigm and predictions for cognitively induced amnesia. Participants first study two series of word-object pairs (in the form of double-cue/one-target) and one series of word-word pairs until they self-report that they could correctly memorize each pair (Phase 1). Participants then perform trials on the third series, which require that they either retrieve (green) or suppress (red) retrieval of the target word in each pair, given the first word (Phase 2). Inserted between these trials are "bystander" words, which are cues from one word-object pair series. Participants judge whether they recognize these cues as old or new. Even/odd buffer judgments are performed before and after bystanders to match the immediate task context across retrieve and suppress trials. We hypothesized that surrounding bystanders with suppression trials affects later memory for bystander targets, causing an amnesic shadow. This is assessed in Phase 3, in which the trained bystander cue and the independent cue that was associated with the bystander target but has not been presented during Phase 2 are used to retrieve the bystander target separately. Memory impairment is predicted for bystander targets under the retrieval of both cues. The cued-recall test assesses the memorability of the learned associations from across the three series, and participants respond by verbally reporting the target object or word.

First, the trained-cue bystander pair series was studied. Thirty word-picture pairs were presented to the participants sequentially, each for 3 s (interstimulus interval = 1 s). Test-feedback cycles followed, in which each cue word was presented alone for up to 5 s and participants judged whether they could retrieve the corresponding target picture or not by pressing one of two keys. Upon key pressing or when the response window expired, the target picture was given at the right side of the cue word for up to 5 s. During this period, participants judged whether they had retrieved the target picture correctly or not by pressing one of two keys. Test-feedback cycles continued on pairs that could not be retrieved until participants indicated that they had successfully recalled 100% of the cue target pairs. Next, the independent-cue bystander pair series was studied, using the same procedure as above. Participants were informed that the target pictures in the first series would be studied again and paired with different cue words. They were explicitly instructed to study the new series without thinking of the first series and to not integrate the three items (i.e., two cue words and one common target picture) into a single memory. Finally, the 30 TNT word-word pairs were studied, using the same procedure as for the bystander pairs.

TNT phase. Cue words from two subsets of the TNT pairs appeared in the TNT phase. Each of the 20 cue words was presented for 6 s either in green (think trial) or in red (no-think trial) font. For think trials, participants were instructed to recall the associated target picture as vividly as possible and to rehearse it silently for the 6-s duration of the trial. For no-think trials, participants were required to avoid thinking about the associated target picture while sustaining their attention on the cue word for the 6-s trial. The standard direct suppression instructions were used (Benoit & Anderson, 2012; Wang et al., 2019): Participants were asked not to replace the target picture with any other diversionary thoughts or images but simply to stop themselves from retrieving the target. Cues from the third subset did not appear in the think or no-think task and served as the control for the TNT manipulation.

To test whether voluntary suppression on one memory affected a different memory, we presented bystander cues between the TNT trials. Notably, only cues from the first bystander series were presented during the TNT phase; they were thus called the trained cues. Cues from the other bystander series did not appear during the TNT phase; they were independent of the TNT manipulation and were thus called the independent cues. The 10 trained cues from one bystander subset were presented between two think trials, serving as probes for retrieval shadow; the 10 trained cues from a second bystander subset were presented between two no-think trials, serving as probes for suppression shadow; the remaining 10 trained cues, from the third bystander subset, did not reappear in the TNT phase and thus served as the baseline for the shadow effect. Each trained bystander cue was presented for 2 s, during which participants internally judged whether they had studied this cue word or not. Notably, no novel words were included as bystanders. Participants were not instructed to retrieve or suppress the target picture for the bystander cue.

Before and after each bystander, we inserted “buffer” intervals during which participants viewed a series of 2–4 digits and decided whether each digit was odd or even. The buffer task ensured that the same task was performed before and after each bystander cue so that a similar transition was made from one task to another (see Hulbert et al., 2016). Therefore, a whole trial was composed of one TNT task, a buffer task, a bystander cue recognition task, another buffer task, and another TNT task. The TNT phase was divided into three sessions, each with four repetitions of the 20 TNT items; because one bystander cue was embedded between two TNT items, each session contained two repetitions of the 20 trained bystander cues. A given bystander was randomly embedded between two TNT items in each repetition.

Test phase. Following the TNT phase, we tested the suppression-induced forgetting effect on the critical TNT pairs and its shadow effect on bystanders. Memory related to the bystanders was tested first. Because the independent cues were not presented during the TNT phase, they should provide a cleaner measurement of target memory change than the trained cues. We therefore tested participants’ memory for the bystander targets using a block design. A cued-recall test was first given to the independent bystander cues. In each trial, the independent cue word was presented on the screen, instructing participants to verbally report its associated target picture within 5 s. After being tested with all independent cues, participants were tested on their memory for the bystander targets with the trained cues, using the same procedure as for the independent-cue test. Finally, the TNT word pairs were assessed via a cued-recall task, with each cue being presented on the screen for 5 s and participants verbally reporting the associated target word. The order of stimuli corresponding to the think, no-think, and control conditions in each word-word/picture series was counterbalanced within and across participants.

Results

Effects of retrieval suppression on the TNT associates. Data from all experiments are available on the Open Science Framework (https://osf.io/gxbfc/). We first tested the suppression-induced forgetting (SIF) effect on the TNT pairs. The percentages of correctly recalled target words (Figure 2A and Table S2) were submitted to a one-factor repeated measures analysis of variance (ANOVA) with three levels (i.e., think, no-think, vs. control). Results showed a significant main effect of suppression status, $F(2, 58) = 5.64$, $p = .006$, $\eta_p^2 = 0.16$.[1] Comparisons between the no-think condition and the control condition revealed significant suppression-induced forgetting, $t(29) = -2.36$, $p = .025$, Cohen’s $d = 0.40$, significant after Bonferroni correction, replicating the classical findings that retrieval suppression impaired memory of the target items. However, no memory improvement was detected for the think condition, think vs. control: $t(29) = 0.78$, $p = .445$, Cohen’s $d = 0.11$. This result verified that the manipulation of retrieval suppression was successful.

Shadow effect of retrieval suppression on bystander associates. We then tested the influence of retrieval suppression on the target memory of the bystander cues. A 2 (Cue Type: trained cue vs. independent cue) × 3 (Suppression Status: think, no-think, and baseline) repeated measures ANOVA was performed on the recall accuracy of the bystander targets (Figure 2B; see Table S1 for detailed results for each condition). Results showed a significant main effect of suppression status, $F(2, 58) = 8.11$, $p = .001$, $\eta_p^2 = 0.22$. Consistent with the pattern of the SIF effect, the overall recall accuracy for bystanders embedded between two no-think trials decreased significantly when compared with the baseline (45.33% vs. 51.83%), $t(29) = -3.24$, $p_{corrected} = .009$, and think (45.33% vs. 53.67%), $t(29) = 3.54$, $p_{corrected} = .004$, conditions; yet no memory improvement was observed for bystanders inserted between two think trials (think vs. baseline: 53.67% vs. 51.83%), $t(29) = 0.85$, $p_{corrected} = 1.00$. Meanwhile, the main effect of cue type was significant, $F(1, 29) = 9.63$, $p = .004$, $\eta_p^2 = 0.25$, with better overall performance in the independent- than trained-cue condition, which might be due to the recency effect and less retroactive interference as the independent-cue group was always studied after the trained-cue group.

Results showed no significant interaction effect of the two factors, $F(2, 58) = 0.76$, $p = .47$, $\eta_p^2 = 0.03$, suggesting similar shadow effect in the two cue types. However, considering that the trained and independent cues received different treatments—the trained cues were presented in the suppression shadow while the independent cues were not—we tested the effect of each cue type separately. We found a significant main effect for independent-cue retrieval, $F(2, 58) = 5.68$, $p = .006$, $\eta_p^2 = 0.16$, but not for trained-cue retrieval, $F(2, 58) = 1.29$, $p = .282$, $\eta_p^2 = 0.04$. Further analysis on the simple effect of the independent-cue group revealed significant memory impairment for no-think bystanders when compared with the baseline bystanders, $t(29) = -2.94$, $p = .006$, Cohen’s $d = 0.46$. No memory improvement was found for think bystanders, think vs. baseline: $t(29) = 0.50$, $p = .620$, Cohen’s $d = 0.10$. Taken together, retrieval suppression does not only impair the directly suppressed memory but also disrupts other memory via amnesic shadow.

An important concern is that the shadow-induced forgetting on the bystander items might simply be due to distractions following the suppression task. It was necessary to examine whether the shadow-induced forgetting on the bystanders was caused by a different amount of distractions following suppression and retrieval trials. To do this, we analyzed the odd/even judgment task performance on the first and second buffer digits, which were presented right after the think and no-think tasks and before the bystander cues (Tables S3 and S4). The buffer task was not influenced by the think or no-think conditions as the performance on it differed neither in speed, first buffer: $t(29) = -1.49$, $p = .148$, Cohen’s $d = 0.27$; second buffer: $t(29) = -0.91$, $p = .372$,

[1] The sphericity assumption was not violated based on Mauchly’s test. Thus, no corrections were applied.

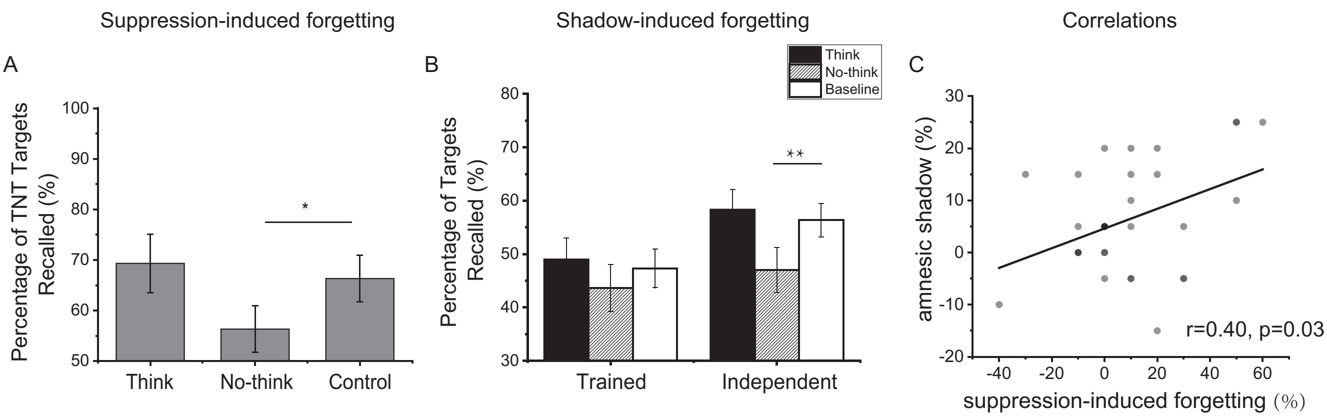

Figure 2. Results for Experiment 1. Panel A: Percentage of targets recalled for the think/no-think (TNT) pairs. Decreased memory performance was found in the no-think condition relative to the control condition, showing the suppression-induced forgetting effect. Panel B: Percentage of targets recalled for the two series of bystander pairs. Significant memory impairment was found in the no-think condition when compared with baseline condition, under independent-cue retrieval. Panel C: Significant correlation between the suppression-induced forgetting effect and the overall amnesic shadow effect of the trained- and independent-cue retrieval. * $p < .05$. ** $p < .01$. (Two-tailed t test.) Error bars indicate standard error of the mean.

Cohen's $d = -0.17$, nor accuracy, first buffer: $t(29) = 1.48$, $p = .149$, Cohen's $d = 0.27$; second buffer: $t(29) = 0.10$, $p = .918$, Cohen's $d = 0.02$, as a function of whether it was performed after a retrieval or suppression trial. There was a weak trend of slower response after the no-think than after the think task for the first buffer digit ($p = .148$), but the trend faded away quickly and did not exist on the second buffer digit. Therefore, the forgetting effect on the bystanders, which were presented at least after the second buffer digit, was unlikely to be caused by distractions of the suppression task.

Correlation between the SIF and amnesic shadow effect. Hulbert et al. (2016) provided evidence that the shadow effect is predicted by the degree of hippocampal activity decrease. Because the degree of hippocampal activity decrease in the current paradigm is mainly manipulated by retrieval suppression, the degree of suppression-induced forgetting should also predict the amnesic shadow effect. Here, we tested whether retrieval suppression predicted the amnesic shadow effect on existing memory. We performed Pearson correlation between the SIF effect (i.e., control—no-think) on TNT targets and its shadow effect (i.e., baseline—no-think) on bystander targets under trained- and independent-cue retrieval. As expected, the SIF effect was significantly correlated with the overall shadow effect, namely the mean shadow effect of independent- and trained-cue retrieval (Figure 2C), $r(30) = 0.40$, $p = .029$. Because the shadow effect was significant in the independent-cue retrieval, we then performed Pearson correlation between the SIF effect and its shadow effect under independent-cue retrieval. However, it was not significant, $r(30) = 0.21$, $p = .277$.

Experiment 2: Anterograde Amnesic Shadow of Retrieval Suppression

The findings above suggest that it is possible to undermine the retrieval of a memory simply by reactivating it near in time to retrieval suppression. Next, we tested the temporal direction of the shadow effect. We wanted to know whether the amnesic shadow occurs in both the forward and backward temporal directions or not. According to findings in suppression-induced virtual hippocampal amnesia, profound memory loss happened to events occurring both after (anterograde amnesia) and shortly before (retrograde amnesia) the lesion (Hulbert et al., 2016). Considering that associative memories rely on the hippocampus to represent (Eldridge, Knowlton, Furmanski, Bookheimer, & Engel, 2000; Henke, 2010), they are likely to be affected by virtual hippocampal amnesia upon reactivation. We thus hypothesized that if the shadow effect comes from hippocampal dysfunctions due to retrieval suppression, the amnesic shadow is likely to induce bidirectional influence on existing memories. To test the bidirectional influence hypothesis on existing memory, Experiment 2 examined the anterograde influence, and Experiment 3 examined the retrograde influence of amnesic shadow. We compared memory for bystanders that followed (Experiment 2) or preceded (Experiment 3) a single no-think trial to items not abutted by suppression.

Method

Participants and materials. The remaining experiments were specifically designed to follow up the shadow results of Experiment 1. An a priori power analysis was performed on the shadow effect in the independent-cue condition of Experiment 1, which determined the sample size to be 33 to obtain 85% power. Due to counterbalancing constraints, 36 participants were recruited for Experiment 2 (age range 18–20 years, 13 male) and the remaining experiments. Participant sampling was performed separately for each experiment. All participants had normal or corrected-to-normal vision. They had no reported history of head injury, neurological disease, or learning disability and no red/green colorblindness. Participants provided written consent before participation. Experimental procedures were reviewed and approved by the Human Subject Review Committee of the Shaanxi Normal University. The same materials were used as in Experiment 1.

Procedure. The same procedure was used as in Experiment 1, with a few modifications (Figure 3A). In the study phase, participants studied two subsets of TNT pairs, one for the (future) think and one for the (future) no-think task. We did not test the memory performance for the TNT pairs in this experiment, so there was no subset for a (future) control condition in the study phase. In the TNT phase, each trained bystander cue was always presented after a TNT trial and was followed by a fixation point, rather than another TNT trial, for 2 s. To match the total duration of the TNT phase in different experiments, instead of repeating each TNT trial 12 times, the TNT trials repeated eight times in Experiment 2. Notably, with TNT trials being presented on both sides, each bystander item was embedded in the retrieval/suppression shadow for six times in Experiment 1. In contrast, the bystander items were embedded in the retrieval/suppression shadow for eight times in Experiment 2 (and in Experiment 3). In the test phase, memory for the bystander pairs was tested, but the suppression-induced forgetting effect was not examined.

Results

We tested the influence of retrieval suppression on the memory of bystanders presented afterward. A 2 (Cue Type: trained cue vs. independent cue) × 3 (Suppression Status: think, no-think, and baseline) repeated measures ANOVA was performed on the recall accuracy of the bystander targets. Results showed a significant main effect of suppression status (Figure 3B), $F(2, 70) = 4.47$, $p = .015$, $\eta_p^2 = 0.11$, with lower overall recall accuracy for bystanders inserted after no-think trials than that for the baseline condition (48.47% vs. 54.72%), $t(35) = -2.62$, $p_{\text{corrected}} = .020$. No memory improvement was observed for bystanders presented after think trials (think vs. baseline: 53.61% vs. 54.72%), $t(35) = 0.52$, $p_{\text{corrected}} = 1.00$. The main effect of cue type was significant, $F(1, 35) = 11.82$, $p = .002$, $\eta_p^2 = 0.25$, with better overall performance in the independent- than trained-cue condition.

Results showed no significant interaction effect of the two factors, $F(2, 70) = 1.37$, $p = .260$, $\eta_p^2 = 0.04$, suggesting similar shadow effects in the two cue types. Considering that the trained and independent cues received different treatments, we examined the effect of each cue type separately. Similar to Experiment 1, a significant main effect was found for independent-cue retrieval, $F(2, 70) = 4.84$, $p = .011$, $\eta_p^2 = 0.12$, but not for trained-cue retrieval, $F(2, 70) = 0.67$, $p = .515$, $\eta_p^2 = 0.02$. Further analysis on the simple effect of the independent-cue group revealed significant memory impairment for no-think bystanders when compared with the baseline bystanders, $t(35) = -2.60$, $p = .014$, Cohen's $d = 0.43$. No memory improvement was found for think bystanders, think vs. baseline: $t(35) = 0.00$, $p = 1.000$, Cohen's $d = 0.00$. Taken together, retrieval suppression induces anterograde influence on memories cued close in time, and the effect is better revealed by independent retrieval cues.

We examined the buffer task performance right after the think and no-think trials (Tables S3 and S4). The buffer task was not influenced by the think or no-think conditions as the performance on it differed neither in speed, first buffer: $t(35) = 0.114$, $p = .910$, Cohen's $d = 0.02$; second buffer: $t(35) = -0.92$, $p = .363$, Cohen's $d = -0.15$, nor accuracy, first buffer: $t(35) = -0.74$, $p = .465$, Cohen's $d = -0.12$; second buffer: $t(35) = -0.56$, $p = .578$, Cohen's $d = -0.09$, as a function of whether it was performed after retrieval or suppression. This result excluded the possibility that the shadow-induced forgetting on the bystanders was caused

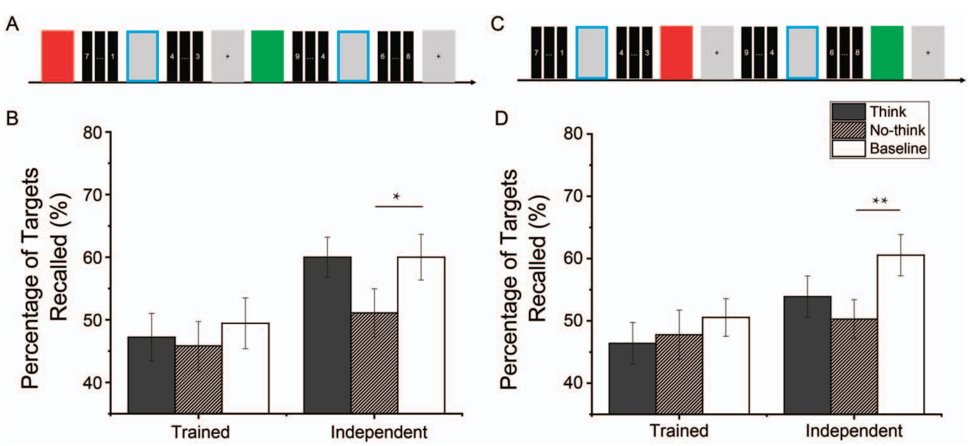

Figure 3. Design and results for Experiments 2 and 3. For illustration purpose, tasks for Experiments 2 (Panel A) and 3 (Panel C) are represented by boxes with different colors: red for the think task, green for the no-think task, gray boxes with blue frames for the bystander task, gray boxes with no frame for the fixation task, and black boxes for the buffer task. Bystander cues are presented after each TNT trial in order to assess the anterograde effect of amnesic shadow in Experiment 2 (Panel A). Panel B: Percentage of targets recalled for the bystander pairs in Experiment 2. Bystander cues are presented before each TNT trial in order to assess the retrograde effect of amnesic shadow in Experiment 3 (Panel C). Panel D: Percentage of targets recalled for the two series of bystander pairs in Experiment 3. Significant memory impairment was found in the no-think condition when compared with baseline condition, under independent-cue retrieval, in both experiments. * $p < .05$. ** $p < .01$. (Two-tailed t test.) Error bars indicate standard error of the mean. See the online article for the color version of this figure.

by a different amount of distractions following suppression and retrieval trials.

Experiment 3: Retrograde Amnesic Shadow of Retrieval Suppression

We then examined the retrograde amnesic shadow effect of retrieval suppression. Each bystander cue was presented before a single TNT trial, and memory for these bystanders was compared to memory of items in the baseline condition.

Method

Thirty-six participants were recruited (age range 17–20 years, 18 male) with the same criterion as in Experiments 1 and 2. The same materials were used as in Experiment 1. The procedure was the same as in Experiment 2, with the only exception that during the TNT phase, each trained bystander cue was always presented before a TNT trial and was preceded by a fixation point to separate different trials (Figure 3C).

Results

We tested whether retrieval suppression could influence memory of bystanders presented beforehand. A 2 (Cue Type: trained cue vs. independent cue) × 3 (Suppression Status: think, no-think, and baseline) repeated measures ANOVA was performed on the recall accuracy of the bystander targets. Results showed a significant main effect of suppression status, $F(2, 70) = 4.56$, $p = .014$, $\eta_p^2 = 0.12$. Again, consistent with the pattern of the shadow effect in previous Experiments 1 and 2, the overall recall accuracy for bystanders presented before no-think trials decreased when compared with the baseline condition (49.03% vs. 55.56%), $t(35) = -2.80$, $p_{corrected} = .019$; no memory improvement but a trend of memory decrease was observed for bystanders inserted before think trials (think vs. baseline: 50.14% vs. 55.56%), $t(35) = -2.26$, $p_{corrected} = 0.066$. The main effect of cue type was marginally significant, $F(1, 35) = 3.65$, $p = .064$, $\eta_p^2 = 0.09$.

Considering that different treatments were given to the trained and independent cues, we tested the effect of each cue type separately. The same result pattern was found as in the anterograde effect (Figure 3D). First, a significant main effect was found for independent-cue retrieval, $F(2, 70) = 4.72$, $p = .012$, $\eta_p^2 = 0.12$, but not for trained-cue retrieval, $F(2, 70) = 0.92$, $p = .404$, $\eta_p^2 = 0.03$. Furthermore, retrieval performance was significantly worse for no-think bystanders when compared with the baseline bystanders, $t(35) = -3.40$, $p = .002$, Cohen's $d = 0.57$, under independent-cue retrieval. No memory improvement but a trend of memory decrease was found for think bystanders, think vs. baseline: $t(35) = -1.84$, $p = .075$, Cohen's $d = 0.31$, under independent-cue retrieval. Taken together, retrieval suppression induces retrograde influence on memory presented close in time.

The meaning of Experiments 2 and 3 is multifold. First, they confirm that the shadow induced by retrieval suppression is able to disrupt unrelated existing memory. Second, they suggest that the amnesic shadow works in both forward and backward temporal directions, which is consistent with the effect being caused by hippocampal dysfunctions (Hulbert et al., 2016). Third, the retrograde effect excludes the possibility that memory lapses were due to differential inattention to bystanders because the bystander cue is given prior to the TNT trial.

Experiment 4: No Impairment When Without TNT Manipulation

Simply presenting the trained cues might already have some influence on the memory of the bystander targets. People might suspect that the amnesia effect could be attributed to memory reactivation on the trained cues, rather than the no-think manipulation. It is known that reactivation often stabilizes its related memory (Rowland & DeLosh, 2014; Zhu et al., 2016), which might cause memory for the trained-cue condition to be strengthened, and such change might even influence independent cues. To exclude the possibility that the shadow effect in above experiments was caused by reactivation on bystanders, we eliminated the TNT procedure by replacing the TNT trials with fixation points. We hypothesized that the reactivation manipulation per se could improve the bystander memory in the trained-cue group, but it does not disrupt the bystander memory at all.

Method

Thirty-six participants were recruited (age range 18–23 years, 15 male) with the same criterion as in the experiments above. The materials were the same as in Experiment 1. The procedure was modified from Experiment 1 (Figure 4A). Although there was no TNT task, items for the TNT task were studied in the study phase. To eliminate the influence of retrieval or suppression, we replaced the TNT trials in Experiment 1 with fixation points, during which

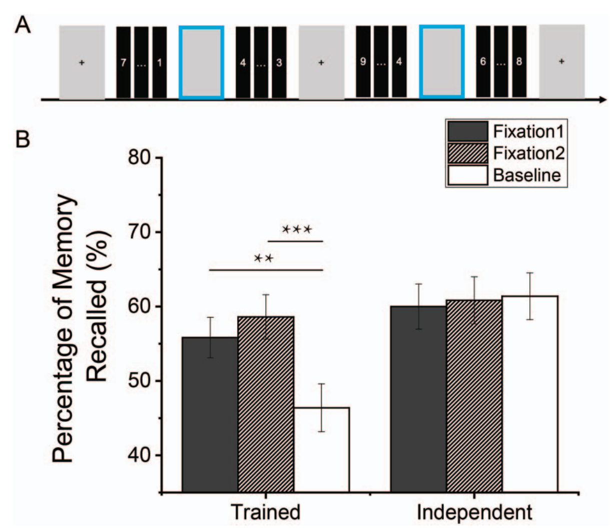

Figure 4. Design and results for Experiment 4. Panel A: Bystander cues (i.e., gray boxes with blue frames in the figure) are presented between fixations instead of TNT trials. Panel B: Percentage of targets recalled for the bystander pairs in Experiment 4. No memory impairment was found on bystander targets when without the influence of amnesic shadow; memory improvement was found under trained-cue retrieval, showing a testing effect. ** $p < .01$. *** $p < .001$. (Two-tailed t test.) Error bars indicate standard error of the mean. See the online article for the color version of this figure.

participants were asked to fixate at a point in the center of the computer screen.

Results

A 2 (Cue Type: trained cue vs. independent cue) $\times$ 3 (Bystander Status: Fixation Group 1, Fixation Group 2, and baseline) repeated measures ANOVA was performed on the recall accuracy of the bystander targets. Note that the same exact fixation task was performed in the Fixation Group 1 and Fixation Group 2 and that they were indistinguishable from one another from the participants' perspective. Results showed a significant main effect of bystander status (Figure 4B), $F(2, 70) = 3.94$, $p = .024$, $\eta_p^2 = 0.10$, and of cue type, $F(1, 35) = 6.14$, $p = .018$, $\eta_p^2 = 0.15$. The interaction effect of the two factors was also significant, $F(2, 70) = 5.04$, $p = .009$, $\eta_p^2 = 0.13$. Simple effects analysis revealed different patterns in the trained- and independent-cue condition. First, a significant main effect was found for trained-cue retrieval, $F(2, 70) = 9.37$, $p < .001$, $\eta_p^2 = 0.21$, showing that the reactivation manipulation alone significantly improved the recall accuracy of the target item, Fixation Group 1 vs. baseline: $t(35) = 2.96$, $p = .005$, Cohen's $d = 0.49$; Fixation Group 2 vs. baseline: $t(35) = 3.80$, $p < .001$, Cohen's $d = 0.63$. In contrast, reactivation did not influence the recall performance under independent-cue retrieval, $F(2, 70) = 0.10$, $p = .904$, $\eta_p^2 = 0.00$; Fixation Group 1 vs. baseline: $t(35) = -0.45$, $p = .656$, Cohen's $d = 0.07$; Fixation Group 2 vs. baseline: $t(35) = -0.29$, $p = .848$, Cohen's $d = 0.03$.

Therefore, reactivation alone did not disrupt the bystander memory; it instead improved the memory under trained-cue retrieval, revealing a testing effect (Rowland & DeLosh, 2014; Zhu et al., 2016). Meanwhile, the memory improvement due to reactivation (as in Experiment 4) was abolished when retrieval suppression was introduced to the trained cues (as in Experiments 1, 2, and 3), which echoes the shadow effect on newly encoded memory (Hulbert et al., 2016) but extends it to the testing effect. This result partly explained the nonsignificant effect in the trained-cue condition. That is, the shadow effect in the trained-cue condition might exist but be masked by the memory improvement effect due to reactivation.

Experiment 5: Forgetting Emotional Memories Through Retrieval Suppression on Neutral Memories

So far, it has been shown that the amnesic shadow induced by retrieval suppression is able to disrupt an unrelated memory reactivated close in time. A unique feature of this amnesic shadow effect is that it disrupts a memory without directly suppressing it. This introduces an idea of dealing with traumatic memories without directly suppressing that memory. This approach would be of great benefit both theoretically and practically. First, transfer of the suppression effect from neutral memories to emotional memories would further support the systemic character of retrieval suppression; second, indirect suppression reduces the chances of reexperiencing traumatic memories and avoids the memory enhancement effect due to memory retrieval. To explore this, we tested whether the amnesic shadow induced by neutral memories is able to disrupt bystander memories with negative emotional values.

Method

Participants and materials. Thirty-six participants were recruited (age range 17–20 years, 12 male) with the same criterion as in the experiments above. The TNT pairs used the same materials as in Experiment 1. For bystander pairs, negative emotional scene pictures were used as targets. Each emotional picture was separately paired with a neutral word (trained cue) and a neutral object picture (independent cue) to compose the double-cue/one-target pairs. The 30 target scenes were selected from the emotional scene pictures in Küpper, Benoit, Dalgleish, and Anderson (2014), which included themes such as physical and sexual assault, witnessing injuries and death, natural disasters, and serious accidents. The scene pictures were originally taken from the International Affective Picture System (Lang, Greenwald, Bradley, & Hamm, 1993) and online sources. The pictures were all negative and carefully matched on valence and arousal by Küpper et al. (2014). In case of cultural differences, we further recruited 50 independent participants to rate the valence and arousal of the scene pictures, which confirmed that the three subsets were matched on valence and arousal across different groups (ps > 0.40). The 30 trained cues were taken from the trained cue words in Experiment 1, which were unassociated with the themes of the scene pictures. The 30 independent cues used the object pictures from the original object-scene pairs in Küpper et al. (2014). Specifically, each object (i.e., independent cue) resembled an item embedded in its paired scene but was not intrinsically related to the scene's gist so that one could not guess the scene given the cue without having initially seen them together (see Figure S1).

Procedure. The procedure for the study and TNT phases was the same as in Experiment 1. In the study phase, participants self-reported memorized the three series of cue-target pairs to 100% accuracy. Because scene pictures were used as targets for bystander pairs, participants were instructed to memorize the pictures as vividly as possible. The TNT task was given to the TNT pairs. In the TNT phase, two subsets of trained cues from the word-scene bystander pairs were presented between two TNT trials; the old/new judgment on the bystander cues was accompanied with key presses, which terminated the cue presentation to avoid excessive exposure to the cue.

In the test phase, memory for the bystander pairs and the TNT pairs was tested in the same order as in Experiment 1. For the bystander test, each object/word cue was presented on the screen for 15 s (interstimulus interval = 3 s), and participants were asked to recall the previously paired scene in as much detail as possible. Scoring was made based on the criterion in Küpper et al. (2014). Two measurements, *identification* and *gist*, were made. In the identification measure, a description was scored as correct if it included enough detail for an independent person to identify the scene. In the gist measure, gist was defined as any element pertaining to the scene's story that could not be changed or excluded without changing the main theme; different from Küpper et al. (2014), in which a description was scored as correct only if it included all necessary elements determined by two independent judges, we calculated the percentage of correctly recollected gist elements for each item. We did not include the detail measure of the scene memory as in

Küpper et al. (2014) for the consideration that the Chinese spoken language does not discriminate certain detail information as in English (e.g., both *he* and *she* are *ta* in oral Chinese). The description was scored by one trained coder who was blind to the conditions to maintain consistency. An independent coder was invited for a subsample of eight participants, which showed high interrater agreement (identification: $r = 1$; gist: $r = .99$). The cued-recall test for the TNT pairs used the same procedure as in Experiment 1.

Results

Effects of retrieval suppression on the TNT associates. We first examined the SIF effect on the TNT pairs. The one-factor repeated measures ANOVA with three levels (i.e., think, no-think, vs. control) showed a significant main effect of suppression status (see Figure 5C; Table S2), $F(2, 70) = 5.52$, $p = .006$, $\eta_p^2 = 0.14$. Comparisons between the no-think condition with the control condition revealed marginally significant suppression-induced forgetting, $t(35) = -1.92$, $p = .063$, Cohen's $d = 0.32$, suggesting that retrieval suppression impaired memory of the target items. However, no memory improvement was detected for the think condition, $t(35) = 1.51$, $p = .139$, Cohen's $d = 0.25$, when compared with the control condition.

Shadow effect of retrieval suppression on bystander associates. We then tested whether retrieval suppression on neutral memories would influence the retrieval of emotional bystanders. A 2 (Cue Type: trained cue vs. independent cue) × 3 (Suppression Status: think, no-think, and baseline) repeated measures ANOVA was performed on the recall accuracy of the bystander pictures. Results showed a significant main effect of suppression status (Figure 5A), $F(2, 70) = 3.46$, $p = .037$, $\eta_p^2 = 0.09$. Consistent with the pattern of the SIF effect, the overall recall accuracy for bystander targets whose cues were embedded between two no-think trials decreased significantly when compared with the baseline condition (72.09 vs. 77.50%), $t(35) = -2.17$, $p_{corrected} = .045$; yet no memory improvement was observed for bystanders between two think trials (think vs. baseline: 76.67% vs. 77.50%), $t(35) = -0.40$, $p_{corrected} = .925$. The main effect of cue type was significant, $F(1, 35) = 98.68$, $p < .001$, $\eta_p^2 = 0.74$, with much better overall performance in the independent- than trained-cue condition. Results showed no interaction effect of the two factors, $F(2, 70) = 0.27$, $p = .764$, $\eta_p^2 = 0.01$. Considering that the

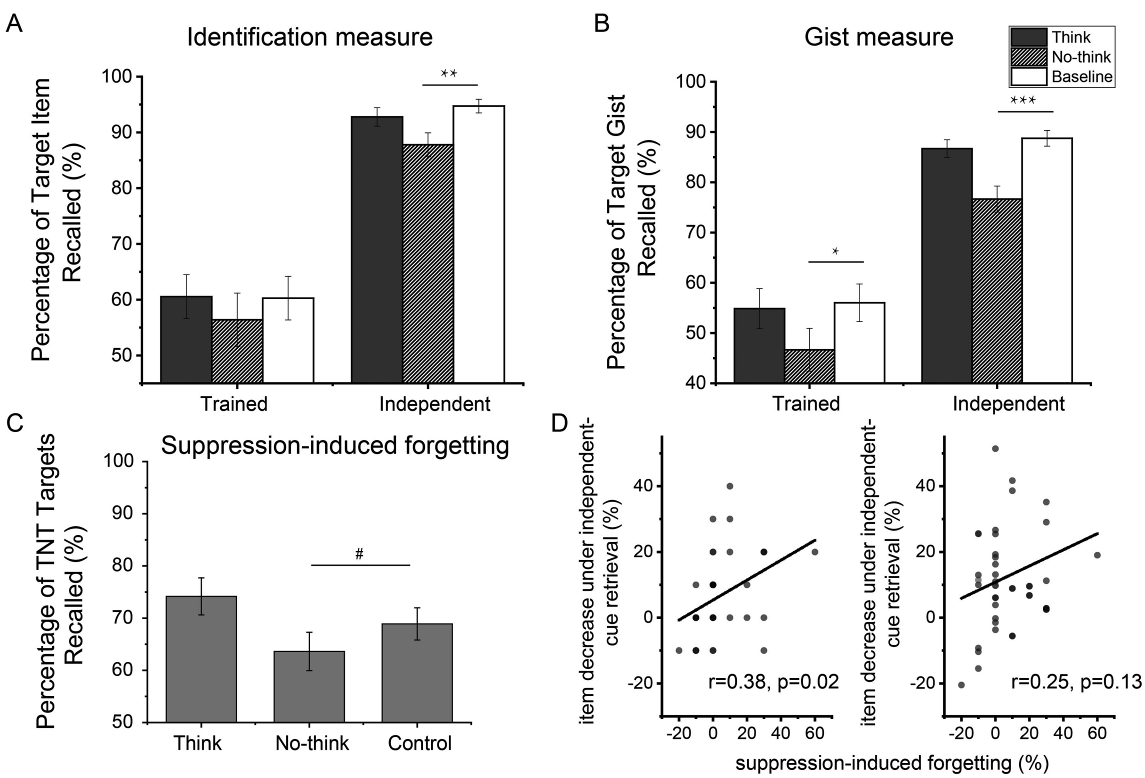

Figure 5. Results for Experiment 5. Panel A: Percentage of target items recalled for the two series of bystander pairs. Significant memory impairment was found in the no-think condition when compared with baseline condition, under independent-cue retrieval. Panel B: Percentage of target gists recalled for the two series of bystander pairs. Significant memory impairment was found in the no-think condition when compared with baseline condition, under both trained- and independent-cue retrieval. Panel C: Percentage of targets recalled for the TNT pairs. Marginal suppression-induced forgetting effect was found in the no-think condition relative to the control condition. Panel D: Correlations between the suppression-induced forgetting effect and the shadow effect in identification (left) and gist (right) measure under independent-cue retrieval. # $p < .07$. * $p < .05$. ** $p < .01$. *** $p < .001$. (Two-tailed t test.) Error bars indicate standard error of the mean.

trained and independent cues received different treatments, we tested the effect of each cue type separately. For independent-cue retrieval, again, a significant main effect was found, $F(2, 70) = 15.9$, $p < .001$, $\eta_p^2 = 0.31$. A simple effects analysis further showed significant lower memory performance for no-think bystanders as compared to the baseline bystanders, $t(35) = -3.19$, $p = .003$, Cohen's $d = 0.53$. No memory improvement was found for think bystanders, think vs. baseline: $t(35) = -1.00$, $p = .324$, Cohen's $d = 0.17$. The main effect for trained-cue retrieval was also significant, $F(2, 70) = 3.87$, $p = .026$, $\eta_p^2 = 0.10$, but no significant memory impairment was found for no-think bystanders as compared to the baseline bystanders, $t(35) = -0.91$, $p = .370$, Cohen's $d = 0.15$.

The above results were further confirmed by analysis on the gist score of the recall responses (Figure 5B). Repeated measures ANOVA found a significant main effect of suppression status, $F(2, 70) = 13.17$, $p < .001$, $\eta_p^2 = 0.27$, with significant memory decrease for no-think bystanders (no-think vs. baseline: 61.66% vs. 72.39), $t(35) = -4.09$, $p < .001$, and cue type, $F(1, 35) = 103.00$, $p < .001$, $\eta_p^2 = 0.75$. The interaction effect between the cue type and suppression status was not significant, $F(2, 70) = 0.25$, $p = .776$, $\eta_p^2 = 0.01$. When testing each cue type separately, a significant main effect was found for both independent-cue retrieval, $F(2, 70) = 15.90$, $p < .001$, $\eta_p^2 = 0.31$, and trained-cue retrieval, $F(2, 70) = 3.87$, $p = .026$, $\eta_p^2 = 0.10$. Further inspections showed that bystander cues presented between no-think trials caused significant gist memory decrease for its targets under both trained-cue, $t(35) = -2.38$, $p = .023$, Cohen's $d = 0.40$, and independent-cue retrieval, $t(35) = -4.59$, $p < .001$, Cohen's $d = 0.76$. No retrieval shadow was found for bystanders inserted between think trials, trained-cue condition: $t(35) = -0.28$, $p = .779$, Cohen's $d = 0.05$; independent-cue condition: $t(35) = -1.04$, $p = .305$, Cohen's $d = 0.17$. Therefore, the amnesic shadow induced by suppression on a neutral memory is able to disrupt the gist memory of an unrelated emotional experience.

To check whether retrieval suppression would affect the reactivation of the bystander memory, we then tested the recognition accuracy and response time for the bystander cues presented between think and no-think trials. We did not find significant differences between the think and no-think bystanders on either the recognition accuracy (think vs. no-think: 83.89% vs. 84.31%), $t(35) = -0.36$, $p = .724$, Cohen's $d = -0.06$, or the response time (think vs. no-think: 1.06 vs. 1.05), $t(35) = -0.67$, $p = .507$, Cohen's $d = 0.11$. However, since we did not include novel items for the recognition task, this might be due to low sensitivity of the recognition task.

To examine whether the shadow-induced forgetting on the bystander items was due to distractions following suppression trials, we examined the buffer task performance (Tables S3 and S4), which was right after the think or no-think task. A trend of difference was found for the first buffer digit on response time, but the difference faded away quickly and did not exist for the second buffer digit, first buffer: $t(35) = -1.74$, $p = .091$, Cohen's $d = -0.29$; second buffer: $t(35) = -0.50$, $p = .618$, Cohen's $d = -0.08$. We did not find significant differences between the think and no-think buffers on response accuracy, first buffer: $t(35) = 0.88$, $p = .385$, Cohen's $d = 0.15$; second buffer: $t(35) = 0.00$, $p = 1.000$, Cohen's $d = 0.00$. Therefore, participants were unlikely to be differentially distracted by the suppression or retrieval tasks during bystander presentation. These results are consistent with the suppression explanation of the shadow-induced forgetting.

Larger SIF was accompanied with larger shadow effect. Next, we tested the correlation between the SIF effect and the shadow effect on the emotional memories. The correlation between the SIF effect (i.e., control—no-think) on TNT targets and the overall shadow effect, the mean shadow effect (i.e., baseline—no-think) of independent- and trained-cue retrieval on bystander targets, was not significant in either identification, $r(36) = 0.18$, $p = .391$, or gist score, $r(36) = 0.08$, $p = .662$. Because the shadow effect is more consistently detected in independent-cue retrieval, we then performed Pearson correlation between the SIF effect and its shadow effect under independent-cue retrieval (Figure 5D). Results showed significant positive correlation between SIF and the shadow effect under independent-cue retrieval for recall accuracy of bystander targets, $r(36) = 0.38$, $p = .021$; the correlation between SIF and the shadow effect in gist score was also positive but did not reach significance, $r(36) = 0.25$, $p = .134$. The correlation highlights that the memory impairment on the bystander pairs is partially determined by the degree of amnesic shadow induced by retrieval suppression.

Discussion

This study provides evidence that an unrelated memory could be disrupted by reactivating it within the amnesic shadow induced by retrieval suppression on an unrelated memory. We initiated retrieval suppression on a set of memories using the TNT task and reactivated an unrelated memory simply by inserting their associated cues between suppression trials. Results showed that retrieval suppression not only disrupted the directly manipulated memory but also induced an amnesic shadow that diminished the unrelated memory that had been reactivated between the suppression episodes. This amnesic shadow functions in both forward and backward temporal directions, and its effect is revealed by independent-cue retrieval. Moreover, taking advantage of the amnesic shadow, we managed to induce forgetting on negative memories through retrieval suppression on unrelated neutral memories. These findings support systemic influence of retrieval suppression on hippocampal functions and offer a way to disrupt existing episodic memories strategically.

The double-cue procedure revealed statistically similar effects in the trained- and independent-cue conditions. However, the amnesia effect was not reliably revealed in the trained-cue condition. One possibility is that the amnesic shadow was masked by the testing effect caused by recognition judgment on the bystander cues. Although the testing effect is generally revealed by explicit recall tests, it is also revealed by recognition tests (Rowland, 2014). Consistent with this, when bystander cues were reactivated without the suppression shadow (Experiment 4), a testing effect (i.e., memory improvement) was detected in the trained-cue condition. In contrast, when bystanders were reactivated within the retrieval suppression shadow (Experiments 1–3, 5), no memory improvement was observed any more. As such, the amnesic shadow at least cancelled out the testing effect, an effect that is consistent with the amnesic shadow on memory encoding (Hulbert et al., 2016) and extends it to the testing effect. In such case, the amnesic shadow did disrupt memory for the trained-cue condition, and the amnesia effect occurred in both trained- and independent-cue retrieval. The cue-independent forgetting, as indicated by studies on suppression-induced forgetting (Anderson, 2003; Anderson & Green, 2001), suggests that the bystander target item itself rather than a certain cue-target association was disrupted. This provides additional support for an inhibition account of the amnesic shadow because retrieval suppression, which causes the amnesic shadow, causes cue-independent forgetting and disrupts the target memory itself (Anderson & Green, 2001; Huddleston & Anderson, 2012; Hulbert, Shivde, & Anderson, 2012; Wang et al., 2015).

While the forgetting effect revealed by independent-cue retrieval suggests an inhibitory mechanism of the amnesic shadow, the present findings are susceptible to other explanations. For instance, some may argue that the suppression task is more difficult than the think or fixation task and that the greater task difficulty is the cause for the shadow effect. However, this is unlikely the explanation for the current results. First, performance on the buffer task, the task that immediately followed the TNT task and separated the TNT task from the bystanders, on either the response accuracy or the response time was not different between the think and no-think conditions, suggesting a similar task difficulty of the two tasks. As such, the consistently observed shadow effect in the no-think condition, if being caused by high task difficulty, should also be observed in the think condition. Second, the think task, which is more difficult and demanding than the fixation task, did not cause more shadow effect than the fixation task. Third, the forgetting effect is directly revealed by independent-cue retrieval, which is a characteristic of suppression-induced forgetting but has not been associated with difficulty-related forgetting effects. Finally, the above evidence accords well with the findings of Hulbert et al. (2016), in which task difficulty did not affect the shadow effect on memory encoding. Therefore, we believe that the shadow effect on the existing memory was more likely to be caused by suppression rather than task difficulty.

There are some important boundary conditions for the shadow effect. For instance, by presenting the bystanders only once, Hulbert et al. (2016) found that the shadow effect is reliably revealed in the second rather than the first half of the TNT phase. This suggests that the shadow effect may start to show up only after participants had sufficient practice modulating the hippocampus (Hulbert et al., 2018). The present study adopted a different procedure, which embedded the bystander cues repeatedly between TNT trials. The consistent shadow effect suggests that repeatedly putting an existing memory into the amnesic shadow causes a stable forgetting effect. Considering that the first half of the TNT phase might also induce amnesic shadow, it would be worth testing the extent to which additional presentations increase the forgetting effect. Another important boundary condition demonstrated by Hulbert et al. (2016) is that the shadow effect should only be revealed by hippocampally dependent memory processes (e.g., on tests of source recognition but not item recognition). Based on this, the shadow effect is ideally examined by recall-based tests, and it is important for the bystander task to engage the hippocampus.

As the amnesic shadow was found to function in both forward and backward temporal directions, an interesting question is whether a double-dosage amnesic shadow (e.g., as in Experiment 1) would cause a greater forgetting effect than a single-dosage amnesic shadow (e.g., as in Experiments 2 or 3). Based on Hulbert et al.'s (2016) findings, the double-dosage suppression is likely to cause more hippocampal dysfunction and greater amnesic shadow in memory encoding. In contrast, the double-dosage and single-dosage amnesic shadow showed similar effects in the present study. However, it should be noted that the bystanders under double-dosage amnesic shadow also received fewer repetitions (i.e., six repetitions for Experiment 1) than those under single-dosage (i.e., eight repetitions for Experiments 2 and 3) amnesic shadow. Since the second half of retrieval suppression was found to contribute more to the shadow effect (Hulbert et al., 2016), such differences in the repetition time might reduce the dosage effect. Therefore, the present study could not answer this question directly.

However, before rationalizing that the same effect would apply to the existing episodic memories, some factors need to be considered. For instance, during retrieval suppression, the hippocampal activity could not only be modulated proactively in response to no-think cues to preempt retrieval but also be suppressed reactively to purge involuntary memory intrusions (Hulbert et al., 2018; Levy & Anderson, 2012). That is, memories that momentarily intrude into awareness reactively trigger inhibitory control during retrieval suppression. If the amnesic shadow shared the mechanism of retrieval suppression, then the shadow effect on an existing bystander memory may rely on intrusions of that memory, which is a different mechanism from the shadow effect on the encoding process. However, retrieval suppression also decreases memory intrusion, which in turn decreases the likelihood of triggering further memory suppression (Anderson & Hanslmayr, 2014; Benoit, Hulbert, Huddleston, & Anderson, 2015; Levy & Anderson, 2012). Under such circumstances, the second dosage of suppression in a double-dosage procedure may have a smaller effect than the first dosage. This also predicts that the degree of bystander memory intrusion, which is not only a hippocampally dependent process but also a prerequisite for retrieval suppression to occur, influences the shadow effect. Based on this, the magnitude of the amnesic shadow effect might be dependent on both the degree of retrieval-induced suppression and the intrusion of the bystander memory, which partly explains why Experiment 1 did not observe a significant correlation between the amnesic shadow and retrieval-induced suppression in the independent-cue group. These questions could be explored by future studies. Figuring them out would help optimize the amnesic shadow effect.

The amnesic shadow might also influence items that were not in the suppression episodes. In the retrograde amnesia study (i.e., Experiment 3), a trend of memory decrease was found for bystanders whose cues were presented before think items. In accordance, across the four main experiments, we did not observe memory improvement in bystander targets due to the retrieval shadow. Notably, the retrieval shadow was not directly tested in Hulbert et al. (2016) as they did not include a control condition as in the present study. However, based on one experiment (i.e., Experiment 5) that included a phonological rehearsal task on nonsense words as a baseline condition, the retrieval shadow, unlike the suppression shadow, only rose to the level of a nonsignificant trend in their study. This is also reflected by the lack of memory improvement effect for think targets due to retrieval practice in Experiments 1 and 5 of the current study. One possible reason is that the amnesic shadow induced by retrieval suppression leaks to unrelated items independent of what task was performed on the items. The leak may depend on how close in time the memory is to the suppression episodes. A comparison between our and Hulbert et al.'s (2016) study suggests that repeatedly presenting items within the shadow might induce broader influence. Therefore, widespread forgetting can be realized through cognitively induced amnesia.

This forgetting mechanism shows potential in dealing with daily life and perhaps traumatic memories. After major traumas, intrusive memories may pervade experience, and failure to cope with their retrieval often causes depressive and stress-related disorders (Brewin, Hunter, Carroll, & Tata, 1996). Yet on the other hand, a certain degree of memory intrusion is a prerequisite for retrieval suppression to function. Plenty of studies have shown that no-think trials with intrusions downregulated hippocampal activity, and the depth of the hippocampal downregulation during intrusions predicted the degree of suppression-induced forgetting (Benoit et al., 2015; Levy & Anderson, 2012). As such, suppression does not work when the unwanted memory intrusion was too strong, while it stops functioning when the intrusion was too weak (Detre, Natarajan, Gershman, & Norman, 2013; Poppenk & Norman, 2014). The HM paradigm may be able to solve these problems. According to the results in Experiment 5, one way is to embed cues of a traumatic memory between the suppression trials targeting arbitrary, controllable memory associates. Because the traumatic memory is not directly suppressed, the current procedure might reduce the risk of triggering full-blown retrieval of the associated traumatic memory. This procedure, despite using materials with different emotional qualities, has been found to cause a similar degree of the amnesic shadow and suppression-induced forgetting when compared with Experiment 1 ($ps > .270$). In the meantime, because any unrelated memories could be used to initiate retrieval suppression, it increases the chance of maintaining a minimum degree of memory intrusion continuously.

However, caution must be taken before translating the HM paradigm into practice. First, the degree to which an amnesic shadow produced by suppressing a neutral memory could be used to forget an emotional memory may be limited. For instance, in Experiment 5, only a weak correlation was found between the effect of retrieval suppression and that of amnesic shadow. This may be due to the emotional and neutral memories relying on different neural mechanisms. While the shadow effect induced by the neutral memory is likely to be represented in the hippocampus, emotional memory reactivation relies not only on the hippocampus but also on emotion-related areas such as the amygdala (Phelps, 2004). Retrieval suppression also recruits different neural mechanisms for emotional memory than for neutral memory (Gagnepain et al., 2017). Second, clinical populations are often hypersensitive to highly intrusive memories; it is unclear whether presenting cues to them would trigger the retrieval of the full traumatic memory (Catarino, Küpper, Werner-Seidler, Dalgleish, & Anderson, 2015; Marzi, Regina, & Righi, 2014; Nørby, 2018). In addition, traumatic memories in daily life are often well consolidated. Future studies could examine whether the amnesic shadow works on well-consolidated episodic memories.

Cognitively induced amnesia carries mechanistic implications for retrieval suppression and practical implications for traumatic memory treatment. The present evidence implies a broad, systemic suppression mechanism: Retrieval suppression disrupts the suppressed content and induces an amnesic shadow that impairs an unrelated existing memory. Our findings also permit inferences about clinical applications of the HM paradigm: This paradigm might provide a way to treat traumatic memory without directly suppressing it and allow consistent memory intrusion to trigger consistent suppression. How exactly the amnesic shadow affects the hippocampal activity sustaining the bystander memory needs further investigation.

References

Anderson, M. C. (2003). Rethinking interference theory: Executive control and the mechanisms of forgetting. *Journal of Memory and Language, 49,* 415–445. http://dx.doi.org/10.1016/j.jml.2003.08.006

Anderson, M. C., & Green, C. (2001). Suppressing unwanted memories by executive control. *Nature, 410,* 366–369. http://dx.doi.org/10.1038/35066572

Anderson, M. C., & Hanslmayr, S. (2014). Neural mechanisms of motivated forgetting. *Trends in Cognitive Sciences, 18,* 279–292. http://dx.doi.org/10.1016/j.tics.2014.03.002

Anderson, M. C., Ochsner, K. N., Kuhl, B., Cooper, J., Robertson, E., Gabrieli, S. W., . . . Gabrieli, J. D. E. (2004). Neural systems underlying the suppression of unwanted memories. *Science, 303,* 232–235. http://dx.doi.org/10.1126/science.1089504

Benoit, R. G., & Anderson, M. C. (2012). Opposing mechanisms support the voluntary forgetting of unwanted memories. *Neuron, 76,* 450–460. http://dx.doi.org/10.1016/j.neuron.2012.07.025

Benoit, R. G., Hulbert, J. C., Huddleston, E., & Anderson, M. C. (2015). Adaptive top-down suppression of hippocampal activity and the purging of intrusive memories from consciousness. *Journal of Cognitive Neuroscience, 27,* 96–111. http://dx.doi.org/10.1162/jocn_a_00696

Brewin, C. R., Hunter, E., Carroll, F., & Tata, P. (1996). Intrusive memories in depression: An index of schema activation? *Psychological Medicine, 26,* 1271–1276. http://dx.doi.org/10.1017/S0033291700035996

Catarino, A., Küpper, C. S., Werner-Seidler, A., Dalgleish, T., & Anderson, M. C. (2015). Failing to forget: Inhibitory-control deficits compromise memory suppression in posttraumatic stress disorder. *Psychological Science, 26,* 604–616. http://dx.doi.org/10.1177/0956797615569889

Depue, B. E., Banich, M. T., & Curran, T. (2006). Suppression of emotional and nonemotional content in memory: Effects of repetition on cognitive control. *Psychological Science, 17,* 441–447. http://dx.doi.org/10.1111/j.1467-9280.2006.01725.x

Detre, G. J., Natarajan, A., Gershman, S. J., & Norman, K. A. (2013). Moderate levels of activation lead to forgetting in the think/no-think paradigm. *Neuropsychologia, 51,* 2371–2388. http://dx.doi.org/10.1016/j.neuropsychologia.2013.02.017

Eldridge, L. L., Knowlton, B. J., Furmanski, C. S., Bookheimer, S. Y., & Engel, S. A. (2000). Remembering episodes: A selective role for the hippocampus during retrieval. *Nature Neuroscience, 3,* 1149–1152. http://dx.doi.org/10.1038/80671

Gagnepain, P., Henson, R. N., & Anderson, M. C. (2014). Suppressing unwanted memories reduces their unconscious influence via targeted cortical inhibition. *Proceedings of the National Academy of Sciences of the United States of America, 111,* E1310–E1319. http://dx.doi.org/10.1073/pnas.1311468111

Gagnepain, P., Hulbert, J., & Anderson, M. C. (2017). Parallel regulation of memory and emotion supports the suppression of intrusive memories. *The Journal of Neuroscience, 37,* 6423–6441. http://dx.doi.org/10.1523/JNEUROSCI.2732-16.2017

Henke, K. (2010). A model for memory systems based on processing modes rather than consciousness. *Nature Reviews Neuroscience, 11,* 523–532. http://dx.doi.org/10.1038/nrn2850

Huddleston, E., & Anderson, M. C. (2012). Reassessing critiques of the independent probe method for studying inhibition. *Journal of Experi-*

mental Psychology: Learning, Memory, and Cognition, 38, 1408–1418. http://dx.doi.org/10.1037/a0027092

Hulbert, J. C., Henson, R. N., & Anderson, M. C. (2016). Inducing amnesia through systemic suppression. *Nature Communications, 7,* 11003. http://dx.doi.org/10.1038/ncomms11003

Hulbert, J. C., Hirschstein, Z., Brontë, C. A. L., & Broughton, E. (2018). Unintended side effects of a spotless mind: Theory and practice. *Memory, 26,* 306–320. http://dx.doi.org/10.1080/09658211.2017.1354999

Hulbert, J. C., Shivde, G., & Anderson, M. C. (2012). Evidence against associative blocking as a cause of cue-independent retrieval-induced forgetting. *Experimental Psychology, 59,* 11–21. http://dx.doi.org/10.1027/1618-3169/a000120

Kim, K., & Yi, D.-J. (2013). Out of mind, out of sight: Perceptual consequences of memory suppression. *Psychological Science, 24,* 569–574. http://dx.doi.org/10.1177/0956797612457577

Küpper, C. S., Benoit, R. G., Dalgleish, T., & Anderson, M. C. (2014). Direct suppression as a mechanism for controlling unpleasant memories in daily life. *Journal of Experimental Psychology: General, 143,* 1443–1449. http://dx.doi.org/10.1037/a0036518

Lang, P. J., Greenwald, M. K., Bradley, M. M., & Hamm, A. O. (1993). Looking at pictures: Affective, facial, visceral, and behavioral reactions. *Psychophysiology, 30,* 261–273. http://dx.doi.org/10.1111/j.1469-8986.1993.tb03352.x

Levy, B. J., & Anderson, M. C. (2012). Purging of memories from conscious awareness tracked in the human brain. *The Journal of Neuroscience, 32,* 16785–16794. http://dx.doi.org/10.1523/JNEUROSCI.2640-12.2012

Marzi, T., Regina, A., & Righi, S. (2014). Emotions shape memory suppression in trait anxiety. *Frontiers in Psychology, 4,* 1001. http://dx.doi.org/10.3389/fpsyg.2013.01001

Nørby, S. (2018). Forgetting and emotion regulation in mental health, anxiety and depression. *Memory, 26,* 342–363. http://dx.doi.org/10.1080/09658211.2017.1346130

Phelps, E. A. (2004). Human emotion and memory: Interactions of the amygdala and hippocampal complex. *Current Opinion in Neurobiology, 14,* 198–202. http://dx.doi.org/10.1016/j.conb.2004.03.015

Poppenk, J., & Norman, K. A. (2014). Briefly cuing memories leads to suppression of their neural representations. *The Journal of Neuroscience, 34,* 8010–8020. http://dx.doi.org/10.1523/JNEUROSCI.4584-13.2014

Rowland, C. A. (2014). The effect of testing versus restudy on retention: A meta-analytic review of the testing effect. *Psychological Bulletin, 140,* 1432–1463. http://dx.doi.org/10.1037/a0037559

Rowland, C. A., & DeLosh, E. L. (2014). Benefits of testing for nontested information: Retrieval-induced facilitation of episodically bound material. *Psychonomic Bulletin & Review, 21,* 1516–1523. http://dx.doi.org/10.3758/s13423-014-0625-2

Schmitz, T. W., Correia, M. M., Ferreira, C. S., Prescot, A. P., & Anderson, M. C. (2017). Hippocampal GABA enables inhibitory control over unwanted thoughts. *Nature Communications, 8,* 1311. http://dx.doi.org/10.1038/s41467-017-00956-z

Wang, Y., Cao, Z., Zhu, Z., Cai, H., & Wu, Y. (2015). Cue-independent forgetting by intentional suppression - Evidence for inhibition as the mechanism of intentional forgetting. *Cognition, 143,* 31–35. http://dx.doi.org/10.1016/j.cognition.2015.05.025

Wang, Y., Luppi, A., Fawcett, J., & Anderson, M. C. (2019). Reconsidering unconscious persistence: Suppressing unwanted memories reduces their indirect expression in later thoughts. *Cognition, 187,* 78–94. http://dx.doi.org/10.1016/j.cognition.2019.02.016

Zhu, Z., Wang, Y., Cao, Z., Chen, B., Cai, H., Wu, Y., & Rao, Y. (2016). Cue-independent memory impairment by reactivation-coupled interference in human declarative memory. *Cognition, 155,* 125–134. http://dx.doi.org/10.1016/j.cognition.2016.06.015

Zhu, Z., Wang, Y., Jia, J., & Wu, Y. (2019). Beta and alpha desynchronizations underlie reconsolidation-mediated episodic memory updating. *Neuropsychologia, 132,* 107135. http://dx.doi.org/10.1016/j.neuropsychologia.2019.107135

Received August 26, 2019
Revision received March 15, 2020
Accepted March 20, 2020 ■