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## Acknowledgements

We thank D. Osorio for help with colour registration; E. Ting, P. Y. Cheng, I. C. Bruce, R. T. Corlett, L. Ramsden, N. Yamashita and A. Walker for comments, P. Kagoro, B. Balyeganira and M. Musana for field assistance in Uganda; J. Magnay, R. W. Wrangham and C. A. Chapman for logistic support in Uganda; and the Ugandan National Council for Science and Technology, Ugandan Wildlife Authority and Makerere University Biological Field Station for permission to work at Kibale. Supported by Research Grants Council of Hong Kong, National Geographic Society, Sigma Xi, Explorer's Club and Croucher Foundation of Hong Kong.

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# Suppressing unwanted memories by executive control

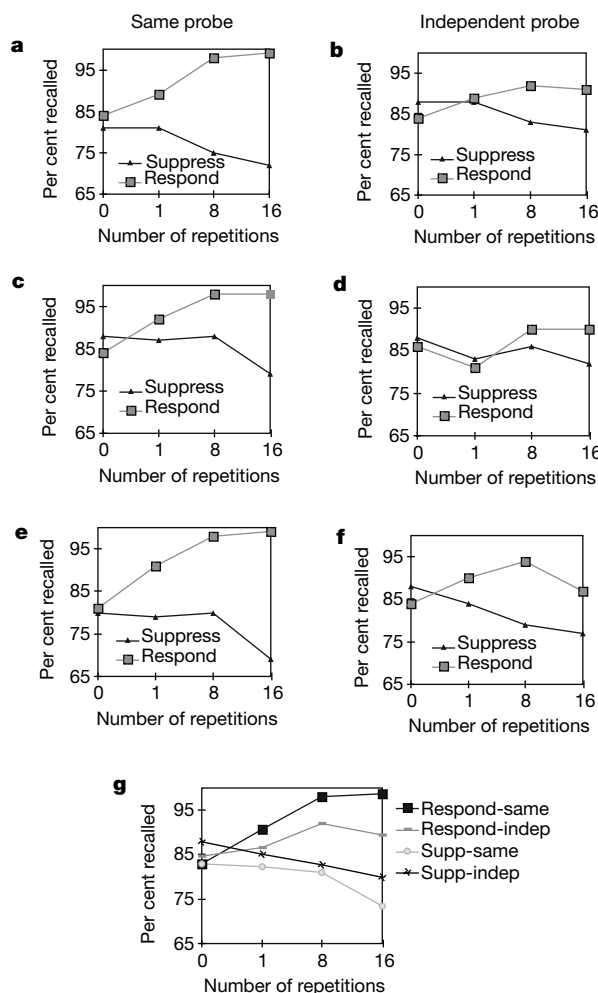
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Freud proposed that unwanted memories can be forgotten by pushing them into the unconscious, a process called repression<sup>1</sup>. The existence of repression has remained controversial for more than a century, in part because of its strong coupling with trauma, and the ethical and practical difficulties of studying such processes in controlled experiments. However, behavioural and neurobiological research on memory and attention shows that people have executive control processes directed at minimizing perceptual distraction<sup>2,3</sup>, overcoming interference during short and long-term memory tasks<sup>3–7</sup> and stopping strong habitual responses to stimuli<sup>8–13</sup>. Here we show that these mechanisms can be recruited to prevent unwanted declarative memories from entering awareness, and that this cognitive act has enduring consequences for the rejected memories. When people encounter cues that remind them of an unwanted memory and they consistently try to prevent awareness of it, the later recall of the rejected memory becomes more difficult. The forgetting increases with the number of times the memory is avoided, resists incentives for accurate recall and is caused by processes that suppress the memory itself. These results show that executive control processes not uniquely tied to trauma may provide a viable model for repression.

Executive control processes studied in behavioural<sup>6,9,14</sup> and neurobiological<sup>2,4,10–13,15–17</sup> research on cognition may provide a mechanism for the voluntary form of repression (suppression)

proposed by Freud<sup>1</sup>. To test this hypothesis, we adapted the go/no-go paradigm used to study executive control over motor actions in primates<sup>18</sup> and humans<sup>15–17</sup> for use in a memory retrieval task. First, we trained subjects on 40 unrelated word pairs (for example, ordeal–roach) so that they could recall the right-hand member of each pair when provided with the left-hand member. Next, subjects performed a critical task requiring them to exert executive control over the retrieval process. On each trial of this think/no-think task, a cue from one of the pairs appeared on the computer screen. Depending on which cue appeared, subjects were told either to recall and say (think about) the associated response word (respond pairs), or not to think about the response (suppression pairs). For the latter pairs, we emphasized that subjects should not allow the associated memory to enter consciousness at all. If subjects accidentally responded to a suppression pair, they heard a beep signalling an error. To increase the need to recruit inhibitory control mechanisms, we required subjects to fixate on the cue word for the entire time (4 s) that it appeared on the screen, discouraging perceptual avoidance and generating a constant threat that the associated memory might intrude into consciousness. Thus, suppression trials required the stopping of both a prepotent motor



**Figure 1** Final recall for respond and suppression items as a function of the number of repetitions for the same-probe (SP) and independent-probe (IP) tests. **a, b**, Experiment 1; **c, d**, experiment 2; **e, f**, experiment 3; **g**, averaged across experiments. Note the negative slope for recall of the suppressed item, indicating increasing inhibition. Inhibition (0 vs 16 suppressions) was significant ( $P < 0.01$ ) in all experiments, and did not interact with type of test cue ( $F < 1$  in all cases; analysis of variance). Inhibition was significant ( $P < 0.05$ ) in every SP and IP test for every experiment (**a–f**).

response and the entrance of an unwanted memory into awareness. Before this phase, we told subjects which cues would require suppression so that they would recognize these words on sight. Subjects performed suppression and respond trials on different pairs that were intermixed. On each trial, no visual marking indicated which cue words were suppression items, forcing subjects to identify each cue to know whether to recall or suppress the associated memory.

The objective of the think/no-think task was to determine whether attempting to prevent awareness of an unwanted memory would hinder its later retrieval. To evaluate whether this occurred, the next phase required subjects to recall the response for each of the cue words. We emphasized that the previous goal of avoiding the associated items was no longer relevant and that a response should be recalled for every cue. If trying to prevent a memory from entering awareness recruits inhibitory control processes that impair that memory's retrievability, recall for suppression items should be worse than for baseline pairs on this test. In all experiments reported here, baseline items were studied pairs that did not appear as either respond or suppression items during the think/no-think phase.

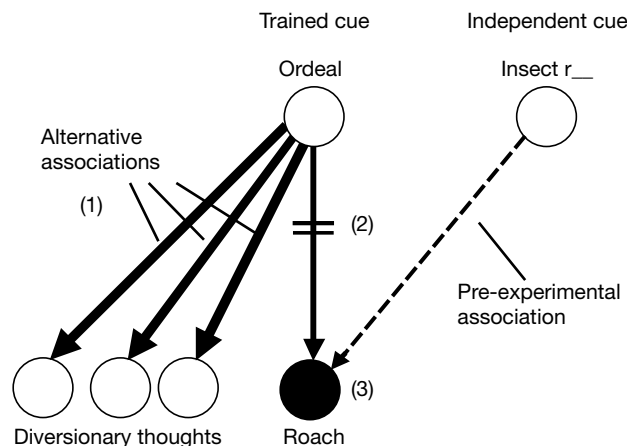
In experiment 1, we varied the number of suppression or respond trials given for each pair. Subjects received 0, 1, 8 or 16 trials for each suppression and each respond item. If excluding unwanted memories from awareness recruits inhibitory control, recall should be worse after 16 suppression attempts than after 0 attempts (baseline). As shown in Fig. 1a, final recall of suppressed items was worse than of baseline items, and impairment increased linearly with suppression practice. In contrast, recall improved across repetitions for respond items, demonstrating the established benefits of retrieving memories on their later recall. These diverging patterns show that controlling awareness not only terminated the powerful facilitative effects of retrieval, but also impaired the recall of suppressed items to below their baseline level (0 suppression attempts). The increasing inhibition with repetition further indicates that unwanted memories might be especially vulnerable in settings requiring protracted avoidance, unlike the modest time (1 min over 16 suppressions) afforded by our task.

Impaired memory for suppression items indicates that there may be an executive control process that suppresses (reduces activation of) the unwanted memory itself (for example, roach in Fig. 2). However, mechanisms other than inhibition may be at work<sup>6</sup>. For instance, one strategy for avoiding an unwanted memory would be to generate diversionary thoughts to environmental stimuli that

remind us of it. New associations between these stimuli and the diversionary thoughts may interfere during later attempts to recall the memory. Alternatively, terminating retrieval may degrade the association between the cue and the response. Neither of these alternatives requires us to assume that the unwanted memory itself is inhibited and thus they do not require the postulation of an executive inhibition process. To isolate the contribution of inhibition, we used the independent probe method<sup>6</sup>. If inhibition impairs the unwanted memory itself, recall should be worse regardless of whether that item is tested with the cue used to train suppression or with a novel cue (Fig. 2). However, associative interference and unlearning predict that forgetting should be limited to the originally trained cue. To distinguish between these models, we retested subjects from experiment 1 with cues not previously encountered in the experiment ('independent probes'). For each item, we cued subjects with a semantic category and the initial letter of the response word (for example, for ordeal—roach, subjects received 'insect r\_\_') and asked them to recall the studied word that fit the cues. On this new independent probe (IP) test, recall of suppressed items was again worse than baseline (Fig. 1b), and the impairment was higher when recall had been avoided more. The amount of forgetting did not differ reliably from when the originally trained cue was used in the test (for example, ordeal in the same probe (SP) test condition, Fig. 1a). This finding rules out associative interference and unlearning and shows that impairment is localized to the unwanted memory itself. This strongly supports the existence of an inhibitory control mechanism<sup>6</sup>.

It was necessary to show that subjects did not recall and then withhold suppression items on the final test. They might have done so out of confusion, given our emphasis on withholding responses during the think/no-think phase. To address this, we expanded our test instructions to emphasize that subjects should recall an item to every cue regardless of earlier instructions, even if they were guessing. To further encourage responding, we offered a monetary reward for correct answers. These incentives had little impact on the inhibition effect (Fig. 1c, d). Impairment was significant overall, increased with repetition, and did not vary with the type of test cue, again supporting the inhibitory control view. Although the instructions to guess enhanced recall of suppression and baseline items when the studied cue was given ( $P < 0.01$ ), the linear trend for inhibition did not differ reliably across experiments ( $F < 1$ ).

Subjects might have guessed the hypothesis of the experiment and tried to conform to the expectation of impaired memory by withholding items. To address this, we altered the final test instructions



**Figure 2** Three mechanisms that can explain impaired recall in the same-probe condition, illustrated with a stimulus pair. Associative interference posits that suppression training leads subjects to generate diversionary thoughts (1) to the trained cue that interfere during later attempts to recall the target. Unlearning assumes that suppression training weakens

the cue–target connection (2). The suppression hypothesis states that suppression training inhibits the target (3). Note that testing the target with an independent cue circumvents interference (1) and unlearning (2). Any impairment found with this test may be attributed to effects localized to the target.

to make subjects believe that we expected improved memory for suppression items. We told subjects that research suggests that when people try not to think about something, they ironically think about it more, as when people try not to think about falling asleep at night and then experience insomnia<sup>19</sup>. We noted that this research predicts that memory for suppression items should improve because the avoided memories should intrude during suppression trials. Post-experimental questionnaires indicated that subjects believed that this was our rationale (average rating of 4.2 on a 5-point belief scale) and most endorsed the theory on the basis of experience. These new test instructions had little effect on the inhibition pattern (Fig. 1e, f).

Success in our think/no-think task is defined by participants' subjective awareness of the unwanted memory during suppression trials, a state which cannot be measured. Efforts to control this state nevertheless left their mark on memory. However, the apparent memory deficit may reflect suppression of the overt motor response associated with the unwanted memory. To test this, we removed the instruction to suppress awareness of the memory during the think/no-think phase. We instead asked subjects to recall the memory, but not say it aloud, rendering this an episodic go/no-go task. Recall did not decline with the number of verbal suppressions, and this pattern did not vary with the cue used to test items (Fig. 3a, b). In contrast, when experiments 1–3 are combined, the linear trend for inhibition was reliable for the SP and IP test conditions ( $P < 0.001$ , Fig. 1g) and these effects did not vary reliably across experiments. Importantly, the linear inhibition effect was statistically larger in the think/no-think task (experiments 1–3) than in the go/no-go task (experiment 4). These findings isolate impaired recall of unwanted memories to cognitive operations directed at keeping them out of awareness.

Our results imply that a process exists that impairs the retention of memories when they are deliberately kept out of consciousness. When people encounter a stimulus that is known to cue an unwanted memory, this process can be recruited to prevent awareness of the memory. The regulation of consciousness is accomplished by an inhibitory control mechanism that suppresses the unwanted memory itself (as shown by our independent probe data), and not merely by the momentary filling of working memory with diversionary thoughts. Delayed recall of the unwanted memory is worse than a baseline condition in which no reminders of the memory were presented in the interim. This paradoxical pattern arises because repeated exposure to reminders makes it necessary for people to adapt their patterns of thought internally with executive control processes. Thus, frequent encounters with reminders should make an unwanted memory less accessible, a finding

noted in some clinical studies of psychogenic amnesia<sup>20</sup>.

Our results clarify the nature and scope of inhibitory processes previously shown to impair episodic recall, and link those processes to behavioural and neurobiological research on executive control. Work on retrieval-induced forgetting<sup>6</sup> has shown that memories that interfere with the retrieval of other targets are inhibited, but it has not previously been established whether inhibition is under strategic control. Research into directed forgetting<sup>7,21,22</sup> suggests a controllable inhibition process, but one limited in scope to an immediately preceding temporal interval. The present findings show a controllable inhibition process that can be flexibly targeted to a specific prepotent memory after intervening memories have been acquired. These findings do not support the popular idea that attempting to suppress an unwanted thought makes it hyperaccessible, at least as this idea applies to suppressing episodic memories<sup>19</sup>.

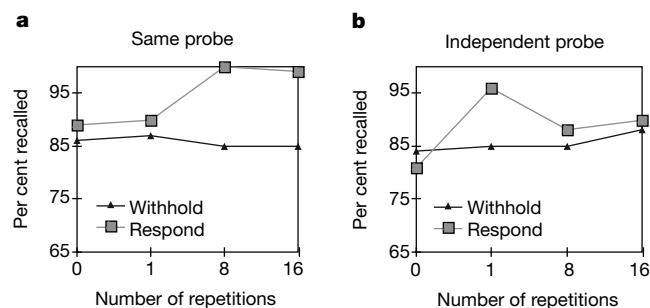
The need to terminate retrieval in the think/no-think paradigm can be viewed as one instance of the need to override prepotent or habitual responses when they are inappropriate, a function presumed to require executive control<sup>4,8–10,12,13,23,24</sup>. Related tasks such as the go/no-go procedure are widely used to study this executive function and have been shown to recruit dorsolateral prefrontal cortex (DLPFC) and anterior cingulate cortex (ACC) (with ventral PFC)<sup>15–17</sup>. Other studies show a specific role of DLPFC in overcoming interference from competing representations in working memory<sup>4</sup>, in selecting one item in working memory as the basis for responding<sup>26</sup> and in on-line manipulation of information<sup>27</sup>. The sustained regulation of awareness required by our procedure is likely to use such processes. This suggests that the think/no-think task recruited DLPFC and ACC, perhaps with medial temporal regions, to control awareness of the memory<sup>28,29</sup>. If this is true, the present memory deficits provide a behavioural marker of the action of this network on rejected memories and suggest that this network exerts control through inhibition<sup>4,6,11,12,25</sup>.

Whatever their neural basis, our results establish a direct link between internal operations that control phenomenal awareness of a memory and its later accessibility. These findings thus support a suppression mechanism that pushes unwanted memories out of awareness, as posited by Freud. Research on retrieval-induced forgetting shows that suppression can have a lasting impact on a memory's accessibility<sup>6</sup>. Suppression in the current paradigm may be similarly enduring. Furthermore, if retrieving diversionary thoughts becomes habitual, inhibition may be sustained without any intention of avoiding the unwanted memory<sup>30</sup>. Together, these factors provide a viable model of repression, and its potential evolution from an intentional to an unintentional process. If so, repression may not be tied uniquely to psychological defence, but may rather reflect the action of a general executive control process, directed at declarative memories of past experience. □

## Methods

Thirty-two neurologically normal college students participated in each experiment, except experiment 4, in which there were sixteen. Each participant was trained on 40 critical and 10 filler word pairs. The stimulus and response members of each pair had a weak pre-experimental relationship, and were unrelated to words in other pairs. The response members were chosen so that each was a member of its own category (for example, insects), to permit later testing of that item with an extralist category cue. The word pairs were exposed individually for 5 s in the centre of a computer screen with the response printed to the right of the stimulus. Test–feedback cycles followed in which subjects were presented with the stimulus member and asked to say the response aloud as quickly as possible. The correct answer was given visually if the response was omitted. Test–feedback cycles on all the pairs continued until a minimum of 50% of the pairs were correctly recalled.

After initial study, subjects were given the think/no-think phase instructions, and were then presented with the 15 stimulus members from the to-be-suppressed pairs without their responses. Subjects familiarized themselves with the stimuli so that they could identify them during suppression trials and prevent the associated memory item from coming to mind. After a brief practice session on the think/no-think task using filler items, subjects were given 377 trials in which respond and suppression stimuli were randomly



**Figure 3** Final recall of withhold and respond items as a function of the number of repetitions. **a**, Performance in the same test probe (SP) condition. **b**, Performance in the independent probe condition (IP). In both conditions, withhold item performance does not decrease with repetition. None of the inhibition effects were significant ( $F < 1$  in all cases). There was reliably more inhibition in experiments 1–3 than in experiment 4 ( $P < 0.05$ ), and a reliably greater linear trend for inhibition ( $P < 0.05$ ). Neither of these tendencies interacted with type of test cue ( $F < 1$ ).

intermixed. On each trial, a fixation cross appeared for 200 ms, followed by a stimulus member in the centre of the screen. For respond trials, the stimulus was presented for up to 4 s, or until the subject responded, and subjects had to report the response as quickly as possible. For suppression trials, the stimulus remained on the screen for 4 s. If a subject responded, a loud error beep sounded. Trials were separated by a 400-ms intertrial interval. Suppression and respond trials were conducted on different word pairs, with five pairs participating in each of the 0 (baseline), 1, 8 and 16-repetition conditions for both the respond and suppression conditions. Respond trials on filler pairs were also included so that 67% of the trials in the think/no-think phase required a response, encouraging a strong mental set to respond that had to be overridden, as in go/no-go tasks.

After the think/no-think phase, we tested the subjects' memory for all of the word pairs in two ways. In both tests, a cue for each word pair was presented in the centre of the screen for up to 4 s, or until subjects spoke the response. Pairs for the different respond and suppress conditions were intermixed pseudo-randomly, with the constraint that the average test position for each condition was equated. In the same-probe test, subjects' recall for each pair was cued with the stimulus member that was paired with the response throughout the experiment. In the independent probe test, subjects were cued with the category name for each exemplar along with its first letter. In each case, subjects were asked to recall the studied item that fit the cues and not to withhold any items. Half of the subjects in each experiment got the same-probe test first, and half were given the independent probe test first.

Subjects in experiment 2 were given 25 cents for each correct answer, up to a maximum of \$4. Subjects in experiment 3 were given a questionnaire after the experiment in which they were asked about their impressions of our (false) hypothesis that memory would improve with attempts to suppress an item.

Received 10 October; accepted 21 December 2000.

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## Acknowledgements

The research reported here was supported by a grant from the US National Institute of Mental Health.

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# Masking unveils pre-amodal completion representation in visual search

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When one object is partly occluded by another, its occluded parts are perceptually 'filled in', that is, the occluded object appears to continue behind its occluder. This process is known as amodal completion<sup>1</sup>. The completion of a partially occluded object takes about 200 ms (ref. 2), and pre-completion information (that is, information from before amodal completion has occurred) exists in the visual system for that duration<sup>2,3</sup>. It has been suggested, however, that observers cannot make use of this information, even when it is beneficial to do so: visual search for a target that appears to be partly occluded, for example, is slower than for a target that does not undergo occlusion, despite both targets being physically identical<sup>4–6</sup>. Here we show that visual search does have access to pre-completion representations, but only for a limited time that depends on the size of the occluded region.

Early investigations of visual search focused on discovering the elementary features available in early vision<sup>7–12</sup>, whereas more recent work has demonstrated that the input to visual search is much more complex than previously assumed<sup>4–6,13,14</sup>. Although it seems that the entry level for vision (that is, entire objects or individual features) can be quite high in many cases, questions remain about the nature of the information available at earlier stages of processing. In the case of amodal completion, for example, it seems that visual search relies on a post-completion representation even when this impairs search<sup>4–6</sup>. This finding can be interpreted in at least three ways. First, it could be that there is no pre-amodal completion stage in processing. This is unlikely because other studies have shown that pre-completion information is available for certain perceptual judgements<sup>2,3</sup>. Second, it is possible that pre-completion information exists only implicitly, as an 'ingredient' in the computation of a completed representation, and is not explicitly available for all perceptual judgements. Examples of this include monocular information during binocular rivalry<sup>15</sup>, and very high spatial frequency information<sup>16</sup>, both of which are present in

**Table 1 Percentage of mean target-absent error rates**

Experiment	Number of items in display			
	2	4	6	8
Medium notch (100-ms SOA)	11.4	17.7	20.3	12.3
Medium notch (250-ms SOA)	3.5	4.6	5.5	3.0
Small notch	18.7	19.8	22.5	15.6
Large notch	2.0	4.0	3.0	1.9