Retrieval Practice Protects Memory Against Acute Stress

Amy M. Smith[1]*, Victoria A. Floerke[1], Ayanna K. Thomas[1]

[1]Tufts University, 490 Boston Avenue, Medford, MA 02155

*Correspondence to: amy.smith@tufts.edu

More than a decade of research has supported a robust consensus: Acute stress impairs memory retrieval. We aimed to determine whether a highly effective learning technique could strengthen memory against the negative effects of stress. To bolster memory, we used retrieval practice, or the act of taking practice tests. Participants first learned stimuli by either restudying or engaging in retrieval practice. Twenty-four hours later, we induced stress in half of the participants and assessed subsequent memory performance. Participants who learned by restudying demonstrated the typical stress-related memory impairment, whereas those who learned by retrieval practice were immune to the deleterious effects of stress. These results suggest that the effects of stress on memory retrieval may be contingent on the strength of the memory representations themselves.

The effects of experimentally induced stress on memory have been studied for more than a decade (*1-7*). The results support a robust consensus: stress impairs memory retrieval (*8*). These studies used a common method whereby participants learn words or images and return 24 hours later for a memory test. Before testing, psychosocial stress is induced. Critically, the memory test is administered ~25 minutes after stress introduction (for exceptions see *5, 6*) when the stress hormone cortisol reaches peak post-stress levels in the blood. Researchers have primarily examined memory after this delay because cortisol has been shown to impact brain regions that are implicated in memory retrieval (*9*).

Previous research on this topic has not been expressly concerned with the quality of encoding during initial learning. Before encoding, participants were typically instructed to "memorize" stimuli. However, the processes that take place at encoding influence memory representation and accessibility (*10*). Without guidance as to how to approach learning material, participants may choose ineffective encoding strategies, resulting in unstable memory representations. Many participants in these preceding studies likely chose to learn by rereading, as this method is often reported as the most popular study strategy (*11*). Rereading is a poor learning strategy, insofar as it creates relatively weak memory representations (*12*). Thus, it is unclear whether all memories are subject to the detrimental effects of stress, or whether only weakly encoded representations are vulnerable.

In our experiment, we addressed this by strengthening memory at encoding through the use of retrieval practice, the act of taking practice tests. Among a host of options for study techniques, we chose retrieval practice for two reasons. First, retrieval practice consistently yielded long-term memory retention that was equal to or better than restudying (*13-15*) and a plethora of other learning strategies such as mental imagery (*12*), concept mapping (*16*), and the keyword mnemonic (*17*). Thus, we chose to use retrieval practice as an encoding technique because it had the most potential to create memories that were resilient to stress. Second, retrieval practice is an easily implemented learning strategy (*12*). We reasoned that if retrieval practice was successful at creating stress-resistant memories, our findings could be readily applied in real-world scenarios (e.g., test anxiety).

A second limitation of previous research on stress and memory concerns the timing of the final memory test. Researchers typically assessed memory 25 minutes after stress induction and found detrimental effects. However, contesting the consensus that stress generally impairs retrieval, recent research showed that participants tested immediately following stress induction exhibited memory performance that was better than or comparable to a no-stress control group (*5, 6*). A secondary aim of the present study was to investigate the potentially facilitative effects of the immediate stress response in the context of a retrieval practice encoding manipulation.

In our experiment, 120 participants studied either 30 concrete nouns or 30 images of nouns, one item at a time. Half of the items in each list were of negative valence and half were of neutral valence. Whether words or images were studied first was counterbalanced. Sixty participants then engaged in *study practice* (SP), in which they restudied the 30 items. The other 60 participants engaged in *retrieval practice* (RP), in which they recalled as many items as they could remember. RP participants were not given feedback on the free recall test or on any subsequent tests. This procedure (item presentation followed by restudy or free recall) was then repeated for the 30 items of the other item-type. Afterward, SP participants restudied all 60 stimuli, whereas RP participants attempted to recall the words and images in any order. After a short distractor task, SP participants again restudied all 60 items and RP participants attempted to recall all items.

Twenty-four hours later, 30 SP and 30 RP participants underwent stress induction and 30 SP and 30 RP participants completed a time-matched non-stressful task. Our encoding and stress manipulations were fully crossed, yielding four between-subjects groups: non-stressed SP, stressed SP, non-stressed RP, and stressed RP. During stress induction, participants gave extemporaneous speeches and solved math problems in front of two judges and three peers (*18*). Measures of physiological arousal confirmed the effectiveness of the stress-induction procedure (*19*). Five minutes into the stress induction or control task, participants completed test 1, in which they recalled either the words or images that were studied the previous day. Test 1 was given to examine memory during the immediate stress response. Twenty minutes later, participants completed test 2, in which they recalled the items that were not assessed on test 1. Test 2 was given to examine memory during the delayed stress response.

The results of our experiment are characterized by three key findings. First, on test 2, stressed SP participants recalled fewer items than non-stressed SP participants (Cohen's *d* effect size (d) = 0.44, 95% CI [0.03, 3.37]), whereas stressed RP participants did not. As seen in Fig. 1, stress resulted in the memory impairment that researchers have repeatedly observed, but only for participants who encoded stimuli via SP. Not only did stressed RP participants outperform non-stressed SP participants (d = 0.61, 95% CI [0.36, 4.37]), they demonstrated recall performance that was similar to non-stressed RP participants, as if stress had not been present.

Second, consistent with one of two recent studies that examined memory performance during both immediate and delayed stress (*6*), we found no difference in memory performance for stressed versus non-stressed participants on test 1. Stress neither impaired nor enhanced memory performance 5 minutes after the onset of stress (Fig. 1). Table 1 provides a more detailed report of test 1 and test 2 performances.

Third, we replicated the robust testing effect (*13, 20*). Participants who encoded via RP recalled significantly more stimuli than those who encoded via SP on test 1 (Partial η^2 effect size (η_p^2) = .06, 95% CI [0.45, 2.77]) and test 2 (η_p^2 = .13, 95% CI [1.38, 3.98]). SP and RP participants respectively recalled, on average, 8.2 and 9.9 items on test 1 and 7.9 and 10.7 items on test 2.

Our results call into question the growing consensus that stress generally impairs memory retrieval. We did not find this effect when (a) stress acted on strong memory representations, or (b) memory was assessed immediately after the onset of stress. Regarding the former, we showed that using a highly effective learning strategy to strengthen memory at encoding inoculated memory against the deleterious effects of the delayed stress response.

A combination of physiological evidence and cognitive theory helps to explain this finding. The delayed stress response is thought to impair retrieval via a physiological mechanism: cortisol binds to glucocorticoid receptors in the hippocampus, impeding retrieval-related processing in this region (*8, 9*). Cognitive theories suggest that retrieval practice is a highly effective learning strategy because it creates multiple routes by which information can be accessed (*14*). When attempting to recall an item from memory, evidence suggests that associated (*21-24*) and/or contextual (*14*) information accompanies that attempt. More retrieval attempts thus create more distinct routes by which the same item can be accessed. Supporting this, a neuroimaging study found that, relative to study practice, retrieval practice increased hippocampal connectivity with other brain regions (*25*). In the case of our study, retrieval practice may have created multiple, contextually-distinct retrieval pathways by which to access information. Although cortisol may have disrupted access to information by certain pathways, the robustness of the memory representation created by retrieval practice may have facilitated access to that information by alternate, undisrupted routes.

The ability for retrieval practice to strengthen memory against stress also has implications for real-world scenarios. For example, strong memory representations may reduce the retrieval failures that are common for students who experience test-related anxiety. Scenarios in which test anxiety impairs memory may thus be re-conceptualized as scenarios that can be avoided when information is well-encoded and accessible via many retrieval pathways.

Our finding that memory was unaffected when tested immediately after stress can likely be attributed to the biphasic nature of the physiological stress response. Immediately after the onset of stress, the body responds with two major hormonal changes: (i) the rapid and short-lived secretion of epinephrine and norepinephrine, and (ii) the gradual and longer-lasting secretion of cortisol (*26*). The former response may facilitate neural processing (*27*), whereas the latter response impedes processing in memory-related brain regions (*9*). Thus, memory may be unchanged or even bolstered immediately after stress.

Several previous studies were unanimous in showing that memory, when measured after a post-stress delay, was impaired by stress. Our results contest this robust finding. Whereas we did find memory retrieval impairment during the delayed stress response when information was encoded by restudying, that impairment was absent when information was encoded by retrieval practice. Thus, we argue that stress may not impair memory retrieval when stronger memory representations are created during encoding. Future research should be geared toward determining the cognitive mechanism by which retrieval practice protects memory against stress. The results of this line of research have the potential to fundamentally transform the way researchers have viewed the relationship between stress and memory.

References and Notes:

1. T. W. Buchanan, D. Tranel, R. Adolphs, Impaired memory retrieval correlates with individual differences in cortisol response but not autonomic response. *Learning & Memory*. **13**, 382-387 (2006).
2. T. W. Buchanan, D. Tranel, Stress and emotional memory retrieval: Effects of sex and cortisol response. *Neurobiology of Learning and Memory*. **89**, 134-141 (2008).
3. V. Hidalgo et al., Acute stress affects free recall and recognition of pictures differently depending on age and sex. *Behavioural Brain Research*. **292**, 393-402 (2015).
4. S. Kuhlmann, M. Piel, O. T. Wolf, Impaired memory retrieval after psychosocial stress in healthy young men. *The Journal of Neuroscience*. **25**, 2977-2982 (2005).
5. P. Schönfeld, K. Ackermann, L. Schwabe, Remembering under stress: Different roles of autonomic arousal and glucocorticoids in memory retrieval. *Psychoneuroendocrinology*. **39**, 249-256 (2014).
6. L. Schwabe, O.T. Wolf, Timing matters: Temporal dynamics of stress effects on memory retrieval. *Cognitive, Affective & Behavioral Neuroscience*. **14**, 1041-1048 (2014).
7. T. Smeets, H. Otgaar, I. Candel, O. T. Wolf, True or false? memory is differentially affected by stress-induced cortisol elevations and sympathetic activity at consolidation and retrieval. *Psychoneuroendocrinology*. **33**, 1378-1386 (2008).
8. L. Schwabe, M. Joëls, B. Roozendaal, O. T. Wolf, M. S. Oitzl, Stress effects on memory: An update and integration. *Neuroscience and Biobehavioral Reviews*. **36**, 1740-1749 (2012).
9. E. R. de Kloet, M. S. Oitzl, M. Joëls, Stress and cognition: Are corticosteroids good or bad guys? *Trends in Neurosciences*. **22**, 422-426 (1999).

10. E. L. Bjork, R. A. Bjork, "Making things hard on yourself, but in a good way: Creating desirable difficulties to enhance learning" in *Psychology and the Real World: Essays Illustrating Fundamental Contributions to Society* (Worth Publishers, New York, NY, 2011), pp. 56-64.
11. J. D. Karpicke, A. C. Butler, H. L. Roediger, Metacognitive strategies in student learning: Do students practise retrieval when they study on their own? *Memory.* **17**, 471-479 (2009).
12. J. Dunlosky, K. A. Rawson, E. J. Marsh, M. J. Nathan, D. T. Willingham, Improving students' learning with effective learning techniques: Promising directions from cognitive and educational psychology. *Psychological Science in the Public Interest.* **14**, 4-58 (2013).
13. H. L. Roediger, J. D. Karpicke, The power of testing memory: Basic research and implications for educational practice. *Perspectives on Psychological Science.* **1**, 181-210 (2006).
14. J. D. Karpicke, M. Lehman, W. R. Aue, "Retrieval-based learning: An episodic context account" in *The Psychology of Learning and Motivation* (Elsevier Academic Press, San Diego, CA, 2014), pp. 237-284.
15. H. L. Roediger, J. D. Karpicke, Test-enhanced learning: Taking memory tests improves long-term retention. *Psychological Science.* **17**, 249–255 (2006).
16. J. D. Karpicke, J. R. Blunt, Retrieval practice produces more learning than elaborate studying with concept mapping. *Science.* **331**, 772-775 (2011).

17. C. O. Fritz, P. E. Morris, M. Acton, A. R. Voelkel, R. Etkind, Comparing and combining retrieval practice and the keyword mnemonic for foreign vocabulary learning. *Applied Cognitive Psychology*. **21**, 499-526 (2007).
18. B. von Dawans, C. Kirschbaum, C., M. Heinrichs, The Trier Social Stress Test for Groups (TSST-G): A new research tool for controlled simultaneous social stress exposure in a group format. *Psychoneuroendocrinology*. **36**, 514-522 (2011).
19. Materials, Methods, and Statistical Analysis are available as supplementary materials in *Science* online.
20. C. A. Rowland, The effect of testing versus restudy on retention: A meta-analytic review of the testing effect. *Psychological Bulletin.* **140**, 1432-1463 (2014).
21. S. K. Carpenter, Cue strength as a moderator of the testing effect: The benefits of elaborative retrieval. *Journal of Experimental Psychology: Learning, Memory, & Cognition.* **35**, 1563-1569 (2009).
22. S. K. Carpenter, Semantic information activated during retrieval contributes to later retention: Support for the mediator effectiveness hypothesis of the testing effect. *Journal of Experimental Psychology: Learning, Memory, & Cognition.* **37**, 1547-1552 (2011).
23. S. K. Carpenter, E. L. DeLosh, Impoverished cue support enhances subsequent retention: Support for the elaborative retrieval explanation of the testing effect. *Memory & Cognition.* **34**, 268-276 (2006).
24. M. A. Pyc, K. A. Rawson, Why testing improves memory: Mediator effectiveness hypothesis. *Science.* **330** (2010).

25. E. A. Wing, E. J. Marsh, R. Cabeza, Neural correlates of retrieval-based memory enhancement: An fMRI study of the testing effect. *Neuropsychologia.* **51**, 2360-2370 (2013).

26. G. S. Everly, J. M. Lating, *A Clinical Guide to the Treatment of the Human Stress Response* (Springer Science + Business Media, New York, NY, ed. 3, 2013).

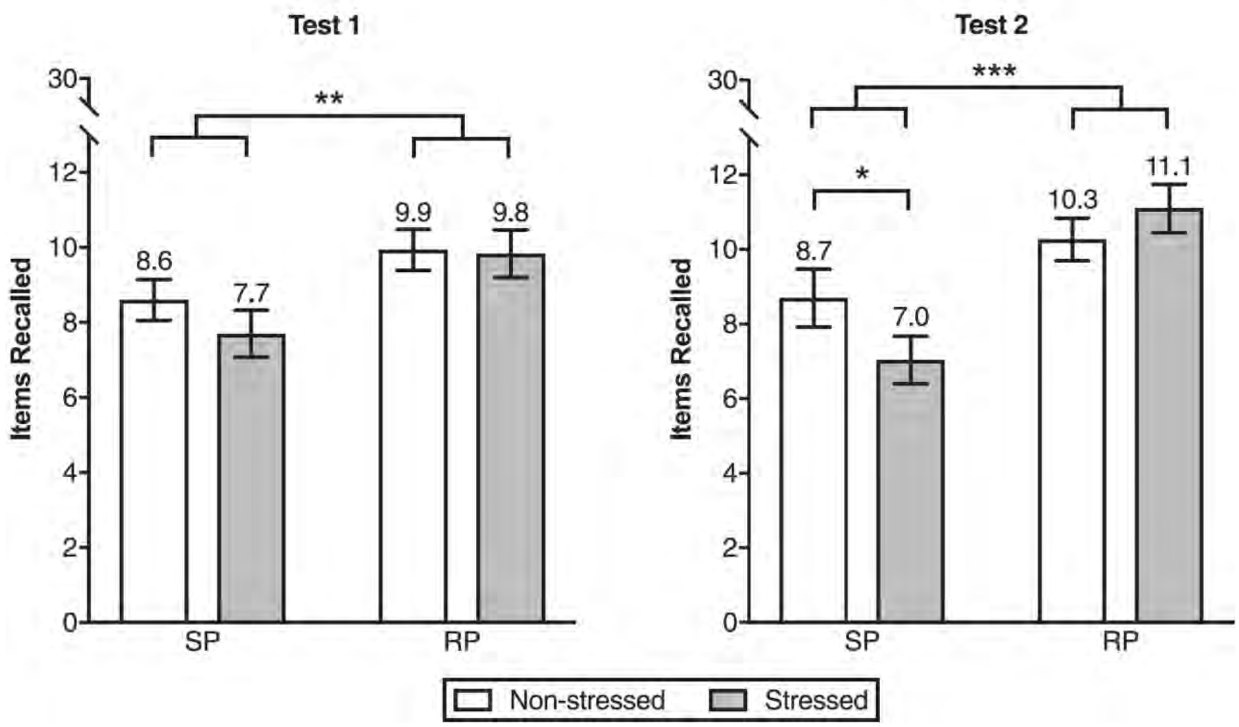
27. E. J. Hermans et al., Stress-related noradrenergic activity prompts large-scale neural network reconfiguration. *Science.* **334**, 1151-1153 (2011).

Acknowledgments:

A full description of the materials, methods, and statistical analyses described in this manuscript is available in the Supplementary Materials. The data described in this paper are available from the first author upon request. This research was funded by the U.S. Army Natick Soldier Research, Development & Engineering Center.

Fig. 1.

Average number of items accurately recalled on tests 1 and 2. Test 1 was administered immediately after the onset of stress. Test 2 followed after a 25 min delay. Retrieval practice (RP) refers to the learning technique in which participants study stimuli and take three subsequent recall tests. Study practice (SP) refers to the learning technique in which participants study stimuli four times. Tests occurred on the day after learning. Error bars represent standard errors of the mean. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.



Test 1	Words		Images	
Group	Negative	Neutral	Negative	Neutral
Non-stressed SP	4.4 *(0.48)*	2.9 *(0.36)*	5.0 *(0.52)*	4.9 *(0.57)*
Stressed SP	3.5 *(0.54)*	2.7 *(0.36)*	5.3 *(0.69)*	3.8 *(0.45)*
Non-stressed RP	4.5 *(0.49)*	4.1 *(0.43)*	6.2 *(0.47)*	5.4 *(0.68)*
Stressed RP	4.6 *(0.58)*	4.1 *(0.36)*	6.3 *(0.79)*	4.9 *(0.29)*
Test 2				
Non-stressed SP	5.3 *(0.61)*	3.9 *(0.74)*	4.5 *(0.68)*	3.8 *(0.50)*
Stressed SP	3.7 *(0.61)*	3.0 *(0.61)*	4.8 *(0.47)*	2.6 *(0.36)*
Non-stressed RP	5.1 *(0.43)*	4.2 *(0.49)*	5.6 *(0.45)*	5.4 *(0.46)*
Stressed RP	5.6 *(0.37)*	5.2 *(0.69)*	6.1 *(0.50)*	5.3 *(0.60)*

Table 1.

Average number of items recalled on test 1 and test 2 as a function of valence and item type.

Tests occurred on the day after learning. Standard errors of the mean are given in parentheses.

Supplementary Materials:

www.sciencemag.org/content/354/6315/1046/suppl/DC1

Materials and Methods

Supplementary Text

Tables S1 to S3

References (28–33)

6 July 2016; accepted 24 October 2016

10.1126/science.aah5067