Research Article

Psychological Science
201X, Vol XX(X) 1–8

DOI: 10.1177/0956797613508789
pss.sagepub.com

Heart Rate Variability Predicts Control Over Memory Retrieval

Brandon L. Gillie, Michael W. Vasey, and Julian F. Thayer
The Ohio State University

Abstract

Stopping retrieval of unwanted memories has been characterized as a process that requires inhibition. However, little research has examined the relationship between control over memory retrieval and individual differences in inhibitory control. Higher levels of resting heart rate variability (HRV) are associated with greater inhibitory control, as indicated by better performance on a number of cognitive, affective, and motor tasks. Therefore, we tested the hypothesis that higher levels of resting HRV predict enhanced memory inhibition as indexed by performance on the think/no-think task. Efforts to suppress no-think word pairs resulted in impaired recall for those items, as in past studies. Moreover, higher levels of resting HRV were associated with more successful suppression, as indicated by lower recall of the to-be-avoided stimuli relative to baseline stimuli. These findings are among the first to suggest that physiological markers of inhibitory control can be used to index a person's capacity to control unwanted memories.

Keywords
memory, response inhibition, self-control, individual differences

Received 1/16/13; Revision accepted 9/20/13

Cognitive-control processes, which facilitate goal-directed actions and suppress inappropriate actions (Braver, Paxton, Locke, & Barch, 2009), are thought to play an important role in managing unwanted thoughts and memories (Banich, Mackiewicz, Depue, Whitmer, & Heller, 2009). One control mechanism is inhibition, the stopping or overriding of a mental process, in whole or in part, with or without intention (MacLeod & Gorfein, 2007). Because people are sometimes motivated to prevent unwanted recall of memories, such as after encountering an unpleasant reminder, it is important to assess the extent to which people can actually use inhibitory mechanisms to stop memory retrieval.

To test this idea, Anderson and Green (2001) developed the think/no-think (TNT) paradigm. In the TNT paradigm, participants learn a list of cue-response word pairs (e.g., "Tape-Radio"). They are then repeatedly presented with the cues studied earlier (e.g., "Tape"). In the think trials, they are asked to think of the response word (e.g., "Radio"). In the no-think trials, they are asked to prevent recall of the response word. Thus, in the latter case, participants attempt to intentionally stop the retrieval of a memory when presented with a cue. Successful suppression of a target memory should reduce its accessibility at a later point; therefore, recall for the response words is assessed at the end of the experiment. A recent meta-analysis of studies in which this paradigm has been used showed that, on average, people tend to have significantly lower recall of no-think items than of baseline items (word pairs that were studied in the initial phase but not presented in the experimental phase; Levy & Anderson, 2008). This finding, known as the *negative-control effect*, is taken to be evidence that people can successfully inhibit retrieval of an unwanted memory and that doing so impairs recall for that particular memory.

Results from recent studies have begun to reveal the neural substrates that underlie control over memory retrieval. Stopping memory retrieval has been characterized as a response override guided by executive-control regions of the brain, such as the prefrontal cortex (Levy & Anderson, 2002). Indeed, Anderson et al. (2004) were

Corresponding Author:
Brandon L. Gillie, Department of Psychology, The Ohio State University, 1835 Neil Ave., Columbus, OH 43210-1222
E-mail: gillie.6@osu.edu

the first to show that participants exhibited increased activity in the bilateral regions of the dorsolateral prefrontal cortex (DLPFC) and the left ventrolateral prefrontal cortex in no-think trials relative to think trials. Other researchers have shown that these prefrontal areas are also involved in stopping retrieval of emotional memories (Depue, Curran, & Banich, 2007). In these studies, memory control was accomplished by activation of the prefrontal regions during suppression attempts, which in turn down-regulated activity in the hippocampus to stop memory retrieval and subsequently impaired later recall (Anderson et al., 2004; Benoit & Anderson, 2012; Depue et al., 2007; Levy & Anderson, 2012). In fact, higher levels of DLPFC engagement during memory suppression correspond to greater hippocampal deactivation and larger memory impairments for to-be-suppressed stimuli (Anderson et al., 2004). Together, these findings suggest that a set of prefrontal areas inhibits brain regions associated with memory retrieval to prevent recall of unwanted memories.

Although suppression of unwanted memories is clearly possible, people differ greatly in their ability to successfully control memory retrieval (Levy & Anderson, 2008). Given that successful suppression depends on activation of prefrontal control regions, some researchers have suggested that the ability to engage executive control more broadly should predict variability in memory suppression (Levy & Anderson, 2008). More specifically, people who are less able to recruit prefrontal areas should show less effective memory suppression in the TNT paradigm. Consistent with this idea, research has shown that age-related changes in prefrontal functionality predict control over memory retrieval such that older adults (ages 65 to 80) show greater difficulty in exerting control over memory retrieval than do young adults (Anderson, Reinholz, Kuhl, & Mayr, 2011). Similarly, people who are affected by executive-control deficits, including those with attention-deficit/hyperactivity disorder, or ADHD (Depue, Burgess, Willcutt, Ruzic, & Banich, 2010) or depression (Hertel & Gerstle, 2003; Hertel & Mahan, 2008), show impaired control over memory retrieval. Thus, individual differences in executive control seem to influence the effectiveness of memory suppression. If so, independent measures of executive-control ability, especially measures of the capacity for inhibitory control, should be useful predictors of the ability to successfully suppress unwanted memories.

One noninvasive and easily obtainable marker of executive-control capacity is heart rate variability (HRV). HRV represents the beat-to-beat changes in heart rate that largely result from the parasympathetic nervous system's tonic, inhibitory influence on the heart via the vagus nerve (Levy, 1990). The vagus nerve is connected to a set of prefrontal areas, including the ventromedial prefrontal cortex (Thayer, Åhs, Fredrickson, Sollers, & Wager, 2012), right DLPFC (Lane et al., 2009; Nugent, Bain, Thayer, Sollers, & Drevets, 2011), and orbitofrontal cortex (Thayer et al., 2012). These areas influence parasympathetic input to the heart such that higher activity in the prefrontal cortex is reflected in the form of higher HRV (Ahern et al., 2001).The prefrontal cortex is able to inhibit the activity of subcortical structures, which allows the organism to respond to demands from the environment and to organize behavior effectively. Because measures of resting HRV can be used to index the activity of this pathway, HRV has been conceptualized as a marker of inhibitory control (Thayer & Lane, 2009).

Moreover, evidence suggests that measures of resting HRV primarily represent a traitlike biomarker (Bertsch, Hagemann, Naumann, Schächinger, & Schulz, 2012), and longitudinal studies have demonstrated the stability of HRV over time (Li et al., 2009). Furthermore, higher levels of resting HRV are associated with better performance on tasks that require inhibition, such as those that assess motor-response control (Krypotos, Jahfari, van Ast, Kindt, & Forstmann, 2011) and those that tap broader executive functions, including working memory (Hansen, Johnsen, & Thayer, 2003) and sustained attention (Johnsen et al., 2003). Hovland et al. (2012) found that performance on executive-function tasks that assess inhibition, attentional shifting, and task switching was correlated with HRV; however, the strongest associations were found for measures of inhibition. These results further suggest that HRV predominantly indexes a person's capacity for inhibitory control.

Neuroimaging research also suggests that HRV may be associated with brain networks that support memory suppression. Paz-Alonzo, Bunge, Anderson, and Ghetti (2013) found that greater functional connectivity in a network involving the DLPFC, cingulate cortex, posterior parietal cortex, and hippocampus predicted successful memory suppression on the TNT paradigm. A number of these structures also play a role in the central autonomic network (Benarroch, 1997), which influences parasympathetic nervous system activity and thus HRV. Indeed, neuroimaging studies have shown that greater regional cerebral blood flow in the right DLPFC and anterior cingulate cortex is linked to higher levels of HRV (Lane et al., 2009). Thus, it is possible that individual differences in HRV indirectly index the functionality of the network that supports successful memory suppression. Despite these associations, it remains unclear whether individual differences in HRV are related to stopping retrieval of unwanted memories.

In the current study, we sought to extend the work in this area by testing the link between resting HRV and the capacity to suppress unwanted memories. We expected that, consistent with previous findings, recall for no-think items would be significantly reduced relative to baseline items, which would indicate that the repeated use of suppression impairs recall for unwanted memories. However, to the extent that memory suppression varies with resting HRV, it should be greater among people with higher resting HRV.

Method

Participants

Eighty-five undergraduate students (mean age = 18.4 years; 63.6% female, 36.4% male) participated in our study. All participants spoke English as a primary language, and none had a previous or current diagnosis of attention-deficit disorder or ADHD. Eight participants were excluded because of noncompliance with the task instructions, as assessed by a postsession questionnaire (M. C. Anderson, personal communication, August, 15, 2012). Two participants were excluded because they failed to learn at least 50% of the experimental words after three study repetitions, which left a final sample of 75 for analyses. All participants received course credit for their participation.

Stimuli

The materials and procedures used were identical to those used in previous TNT studies (e.g., Anderson et al., 2004; Paz-Alonso, Ghetti, Matlen, Anderson, & Bunge, 2009) and were obtained directly from M. C. Anderson (personal communication, August 15, 2012). The stimuli consisted of 57 word pairs (36 critical pairs and 21 filler pairs). Each pair consisted of a cue word and a response word, and all pairs were designed so that the cue word was weakly associated to the response word. The critical word pairs were divided into three stimulus sets of 12 pairs each, which were rotated through think, no-think, and baseline conditions across participants such that each participant received one of three word-list rotations (rotation A: n = 28; rotation B: n = 25; rotation C: n = 22).

Procedure

Before the experimental task, participants provided informed consent and were fitted with surface electrodes and instructed to rest quietly for 5 min. During this time, heart rate was continuously recorded.

The experiment consisted of three phases: study with feedback, TNT, and memory test. During the study-feedback phase, participants were instructed to learn each of the 57 word pairs. Each pair was presented visually, side by side, for 5 s. After the initial presentation, participants' ability to recall the response words was tested. On each trial, the cue word of a pair (e.g., the left-hand word) appeared, and participants were instructed to speak the correct response word (e.g., the right-hand word) into a microphone. Participants were given 4 s to respond; the correct response word was then displayed for 1 s. The study-feedback procedure was repeated up to three times, until participants remembered at least 50% of the critical response words.

On each trial in the TNT phase, a cue word was presented in a red or green typeface on a computer monitor. For green cue words (think trials), participants were instructed to think of the corresponding response word and keep it in mind while the cue was displayed on the screen (4 s). For red cue words (no-think trials), participants were told to pay full attention to each word but to prevent the associated response word from coming to mind at all. Before beginning the actual TNT phase, participants practiced the task on filler word pairs. Afterward, participants were allowed to ask questions and filled out a short diagnostic questionnaire that assessed whether they understood the task instructions. In the actual TNT phase, participants saw four 108-item blocks, for a total of 432 items, in a specific presentation order constructed using block randomization of the stimuli. Each no-think and think cue word was repeated a total of 16 times in the TNT phase. During this phase, the participants were given a short break (45 s) after each block to help them maintain their attention and focus. To further ensure that the participants understood the task instructions, at the halfway point of the TNT phase, we gave participants the same diagnostic questionnaire administered after the practice trials. The entire TNT phase lasted approximately 27 min.

Finally, in the memory-test phase, participants' memory for the response words was tested with an independent-probe (IP) test and a same-probe (SP) test. In the IP test, participants were given a category and the first letter of the correct response word (e.g., "Media-R__"). In the SP test, participants were presented with the original cue ("Tape") and were asked to recall the response word ("Radio"). In each recall test, participants were tested on a total of 40 word pairs: 4 filler items, 12 think items, 12 no-think items, and 12 baseline items (i.e., items that were studied in the first phase of the experiment but were not seen in the TNT phase). Thirty-eight participants received the IP test first, and 37 received the SP test first.[1]

To address the issue of noncompliance with task instructions, Anderson and Huddleston (2011) recommended that experimenters take precautions such as using questionnaires and carefully wording instructions and recruitment materials. In the current study, after the memory-test phase was complete, participants completed a rating scale that assessed their degree of noncompliance with the no-think instructions. We asked participants three questions that assessed the extent to which they made an effort to intentionally think about the responses for the no-think words during the TNT phase. Participants responded on a 5-point scale (0 = *never*, 4 = *very frequently*). We excluded from analyses any participants who obtained a score of 6 or more (*n* = 8). Anderson and Huddleston (2011) suggested that participants who anticipate a final memory test might be less likely to comply with the no-think instructions; therefore, researchers should not mention "memory" or "testing." We therefore made sure that there was no mention of these terms in the experimenter script, consent form, and recruitment paragraph.

HRV

Heart rate was collected by using a standard three-electrode setup. The electrocardiogram (ECG) signal was sampled at a rate of 1000 Hz, with a high-pass filter of 0.5 Hz, and was passed through a BioNex two-slot mainframe (Mindware Technology, Gahanna, OH) to a personal computer. The ECG signal was analyzed off-line using Mindware Technology's HRV analysis software, Version 2.51. This software provides automatic R-peak detection and allows for visual inspection and editing of the ECG signal. Artifact correction was performed for any irregular or ectopic beats. The interbeat-interval time series was written in a single text file and analyzed using the Kubios HRV analysis software, Version 2.0 (Tarvainen, Niskanen, Lipponen, Ranta-aho, & Karjalainen, 2009). This allowed us to obtain estimates of HRV. To obtain frequency-domain indices of HRV, we used autoregressive estimates of high-frequency power (HF-HRV; 0.15–0.40 ms^2/Hz). Higher values of HF-HRV indicate stronger parasympathetic influence on heart rate. Values of HF-HRV were transformed logarithmically (base 10) to better approximate a normal distribution. All procedures were conducted in accordance with the recommendations of Task Force of the European Society of Cardiology and the North American Society of Pacing Electrophysiology (1996).

Results

Results for the two recall tests are presented in Figure 1. To analyze the percentage recall in the SP and IP tests, we first conducted two mixed-design analyses of variance (ANOVAs) with a between-subjects factor of word-list rotation (A, B, C) and a within-subjects factor of instruction (think, no-think, baseline).[2] Planned comparisons were used to assess differences in recall between no-think and baseline items and between think and baseline items.

Results revealed a significant main effect of instruction on both the SP test, $F(2, 144) = 19.18$, mean squared error (MSE) = 1,633.27, $p < .001$, $\eta_p^2 = .21$, and the IP test, $F(2, 144) = 7.77$, MSE = 896.02, $p = .001$, $\eta_p^2 = .09$. Participants recalled fewer no-think items than baseline items (a memory-suppression effect) on both the SP test, $F(1, 72) = 7.39$, MSE = 1,360.27, $p = .008$, $\eta_p^2 = .09$, and the IP test, $F(1, 72) = 10.52$, MSE = 3,070.56, $p = .002$, $\eta_p^2 = .12$. They recalled more think items than baseline items (a facilitation effect) on the SP test, $F(1, 72) = 13.48$, MSE = 1,922.43, $p < .001$, $\eta_p^2 = .15$, but not on the IP test,

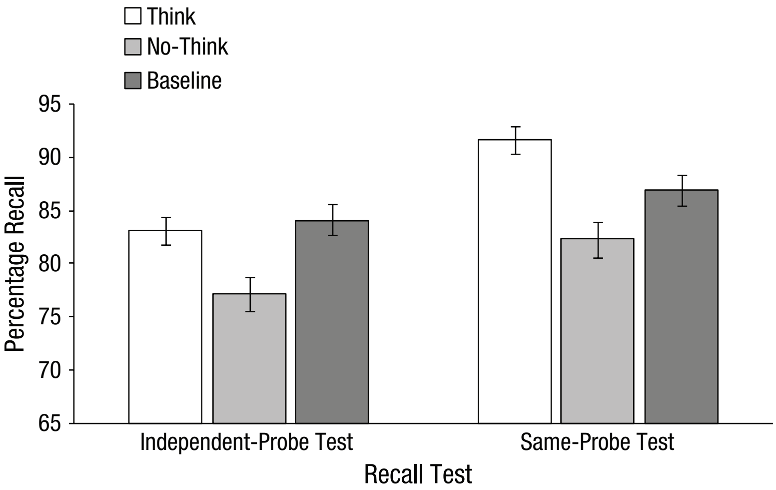

Fig. 1. Percentage recall as a function of test type (independent-probe or same-probe) and item type (think, no-think, or baseline). Error bars indicate ±1 *SEM*.

$F = 0.31$, $p = 0.57$. Both effects were qualified by a significant Instruction × Word-List-Rotation interaction for both the SP test, $F(4, 144) = 3.90$, $MSE = 332.17$, $p = .005$, $\eta_p^2 = .09$, and the IP test, $F(4, 144) = 7.12$, $MSE = 820.50$, $p < .001$, $\eta_p^2 = .16$.

To test the effect of HF-HRV, we compared memory-suppression scores (no-think percentage recall minus baseline percentage recall) between high- and low-HF-HRV groups created through a median split. Specifically, subjects were sorted into high- and low-HF-HRV groups within each word-list rotation. We then combined scores across the word-list-rotation groups to construct high- and low-HF-HRV subgroups. We conducted separate ANOVAs for the SP and IP tests, with between-subjects factors of word-list rotation and HF-HRV group (high, low); for each analysis, the dependent variable was the difference between recall for no-think and baseline words. We found a significant between-subjects effect of HF-HRV group for both the IP test, $F(1, 69) = 11.26$, $MSE = 2{,}941.61$, $p = .001$, $\eta_p^2 = .14$, and the SP test, $F(1, 69) = 4.18$, $MSE = 722.85$, $p = .046$, $\eta_p^2 = .05$, such that the high-HF-HRV group displayed less recall for no-think words relative to baseline words compared with the low-HF-HRV group (Fig. 2). No significant interactions between HF-HRV group and word-list rotation were obtained (both Fs < 1.5).[3]

Discussion

This study is the first to demonstrate an association between HRV and the capacity to suppress unwanted memories. These results inform current understanding of both resting HRV as a marker of cognitive-control ability and inhibition as a key process in stopping memory retrieval. The neurovisceral integration model (Thayer & Lane, 2000) specifies a neural network in which the prefrontal cortex exerts an inhibitory influence on subcortical structures to allow the organism to organize cognitive, affective, and behavioral responses in an adaptive manner. Activity in this network can be indexed by resting HRV level. Our results broaden this conceptualization to include control over memory. Although the TNT paradigm is portrayed as a situation in which inhibitory control is required (Anderson & Huddleston, 2011), it is relatively unclear whether performance on this task generalizes to other tasks or instances in which inhibition is needed (but see Depue et al., 2010). We have clarified this matter by showing that memory deficits in the TNT paradigm are associated with resting HRV level, which provides a general index of inhibitory capacity (Thayer & Lane, 2000). Thus, people who can successfully exert control over memory retrieval are also likely to show enhanced inhibitory control in other response domains, such as motor and affective tasks.

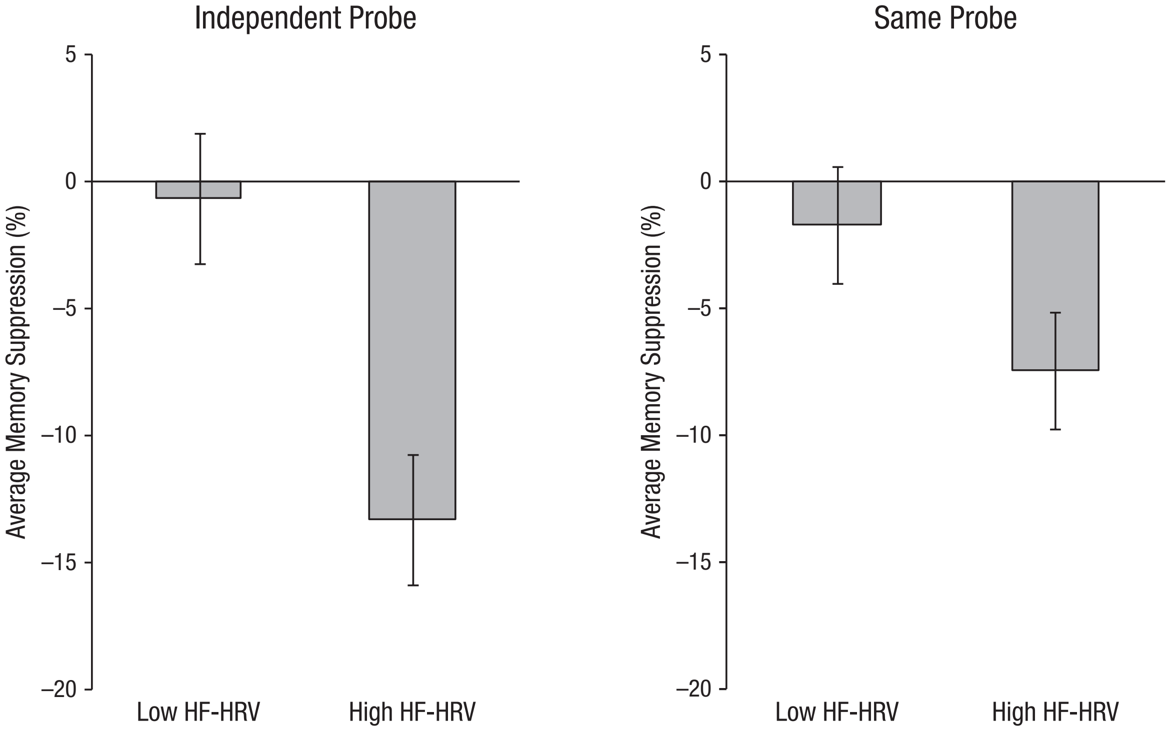

Fig. 2. Average memory suppression on the independent-probe test and same-probe test as a function of high-frequency-power heart rate variability (HF-HRV). Memory suppression was calculated by subtracting the percentage recall for baseline items from the percentage recall for no-think items. HF-HRV groups were formed on the basis of a median split within and across counterbalancing factors. Error bars indicate ±1 *SEM*.

Although the memory suppression observed in the TNT paradigm is thought to result from inhibitory processes, it is important to consider the manner in which the no-think items are tested (Anderson & Huddleston, 2011). When participants are presented with a cue word on the SP test, it is unclear whether forgetting the response word is the result of an inhibitory process or of associative interference from some mental activity or strategy that may have been used during the no-think trials, such as thinking an alternative thought or "mind blanking" (Levy & Anderson, 2008, p. 633). However, this account of forgetting becomes untenable when participants are tested using a novel cue, as in the case of our IP test. For these reasons, memory deficits on the SP test potentially reflect the joint contributions of inhibition and associative interference, whereas performance on the IP test is thought to provide a purer measure of inhibitory control over memory (Anderson & Levy, 2007). We found the strongest association between HRV and memory suppression on the IP test, as should be expected, given that HRV provides an index of inhibitory capacity (Thayer et al., 2012). However, the current findings are correlational; the relationship between HRV and forgetting in the TNT task could reflect the involvement of shared processes other than inhibition, such as attention.

The finding that people differ in the ability to suppress unwanted memories may have important clinical implications. For instance, intrusive memories are a defining feature of posttraumatic-stress disorder (Brewin, Gregory, Lipton, & Burgess, 2010) and play a role in its severity and course, such that higher levels of distress associated with uncontrollable memories at the time of diagnosis predict poorer prognosis 6 months later (Michael, Ehlers, Halligan, & Clark, 2005). Thus, the ability to exert control over unwanted memories seems to be an important factor in maintaining psychological health. Our results imply that clinicians may be better able, compared with current practice, to identify people who struggle with this ability by measuring resting HRV levels. Future studies should examine whether low HRV levels make people more vulnerable to developing disorders associated with memory disturbances because of the connection between low HRV levels and deficits in memory control.

In addition, the association between individual HRV differences and memory suppression may help to explain failures to replicate the expected results of cognitive-control tasks, including the TNT and thought-suppression paradigms. In three experiments that closely paralleled earlier TNT studies, Bulevich, Roediger, Balota, and Butler (2006) found no evidence for a reliable effect of memory suppression. The finding that suppression increases the accessibility of unwanted thoughts, known as the *postsuppression rebound effect* (Wenzlaff & Wegner, 2000), has received mixed support, and some researchers have noted the inconsistencies in this literature (Abramowitz, Tolin, & Street, 2001; Purdon, 2004). These discrepant findings may be due in part to the moderating influence of a third variable, such as HRV. Samples that differ in average resting HRV level, which reflects the capacity for executive control, might also differ in the degree to which suppression is successful.

At minimum, our results suggest that researchers interested in cognitive-control phenomena such as inhibition should account for individual differences in HRV to more clearly estimate their effects. Suppression seems to be an effective strategy for dealing with unwanted memories for people with high HRV levels. It remains to be seen whether treatments designed to increase individual HRV level, such as mindfulness meditation (Tang et al., 2009) and aerobic exercise (Jurca, Church, Morss, Jordan, & Earnest, 2004), might also strengthen the capacity to suppress unwanted memories.

One limitation of the current study is that the persistence of suppression-induced effects of forgetting outside the experimental setting remains unclear. In the TNT paradigm, participants attempt to suppress a number of no-think items, but the total amount of time spent in this effort is limited to 27 min. One can imagine that people who are motivated to avoid unwanted memories in a naturalistic setting engage in suppression more frequently and for a much longer period of time. Currently, it is unknown whether the memory impairment caused by suppression lasts only for a brief period or persists for an extended time. One interesting question is whether people who excel in memory suppression (e.g., people with high resting HRV levels) can keep up such efforts over time and retain the benefits of memory suppression. Future studies should investigate this possibility to provide a better understanding of the potential benefits of motivated suppression. In addition, it is unclear whether the current findings generalize to the suppression of more complex, personally relevant memories. Future studies using the TNT paradigm should address these limitations.

In summary, stopping memory retrieval is an act of cognitive control that requires inhibition. People who can more effectively engage prefrontal areas are better able to successfully suppress unwanted memories. Individual differences in resting HRV can be used to index this capacity; people with higher HRV levels demonstrate greater control over memory. By examining HRV levels, researchers and clinicians should be better able to identify people who are likely to struggle with intrusive thoughts and memories. The ability to choose the thoughts one wants to think has important implications for successful adaption in a complex world. Moreover, these results provide further support that HRV indexes the capacity for cognitive regulation, especially inhibitory control. Researchers should continue to examine individual differences in HRV to better predict self-regulatory success or failure and understand cognitive-control processes.

Author Contributions

B. L. Gillie developed the study concept, collected and analyzed the data, and drafted the manuscript under the supervision of M. W. Vasey and J. F. Thayer.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

Supplemental Material

Additional supporting information may be found at http://pss.sagepub.com/content/by/supplemental-data

Notes

1. The experimental design contained the two crossed conditions of word-list rotation and test order. However, the cell sizes ranged from 7 to 19 participants. Thus, the design was not fully counterbalanced.
2. We first conducted a preliminary analysis in which we tested the between-subjects effect of test order (IP first, SP first). Specifically, we conducted mixed-model ANOVAs in which the between-subjects factor was test order and the within-subjects factor was instruction (i.e., think, no-think, or baseline). Although there was a significant main effect of test order for the IP test, $F(1, 73) = 6.78$, $p = .01$, this effect was not significant for the SP test. Critically, in neither case did test order interact with instruction (ps > .09) Therefore, test order was not included in subsequent analyses.
3. In addition, we conducted hierarchical regression analyses to examine HF-HRV as a continuous predictor of memory suppression. The results of these analyses support the results of the ANOVAs and can be viewed in the Supplemental Material available online.

References

Abramowitz, J. S., Tolin, D. F., & Street, G. P. (2001). Paradoxical effects of thought suppression: A meta-analysis of controlled studies. *Clinical Psychology Review*, *21*, 683–703.

Ahern, G. L., Sollers, J. J., Lane, R. D., Labiner, D. M., Herring, A. M., Weinand, M. E., . . . Thayer, J. F. (2001). Heart rate and heart rate variability changes in the intracarotid sodium amobarbital test. *Epilepsia*, *42*, 912–921.

Anderson, M. C., & Green, C. (2001). Suppressing unwanted memories by executive control. *Nature*, *410*, 366–369.

Anderson, M. C., & Huddleston, E. (2011). Towards a cognitive and neurobiological model of motivated forgetting. In R. F. Belli (Ed.), *Nebraska Symposium on Motivation: Vol. 58. True and false recovered memories: Toward a reconciliation of the debate* (pp. 53–120). New York, NY: Springer.

Anderson, M. C., & Levy, B. J. (2007). Theoretical issues in inhibition: Insights from research on human memory. In D. Gorfein & C. M. MacLeod (Eds.), *Inhibition in cognition* (pp. 81–103). Washington, DC: American Psychological Association.

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.

Anderson, M. C., Reinholz, J., Kuhl, B., & Mayr, U. (2011). Intentional suppression of unwanted memories grows more difficult as we age. *Psychology and Aging*, *26*, 397–405.

Banich, M. T., Mackiewicz, K., Depue, B. E., Whitmer, A., & Heller, W. (2009). Cognitive control mechanisms, emotion and memory: A neural perspective with implications for psychopathology. *Neuroscience & Biobehavioral Reviews*, *33*, 613–630.

Benarroch, E. E. (1997). The central autonomic network. In P. A. Low (Ed.), *Clinical autonomic disorders* (2nd ed., pp. 17–23). Philadelphia, PA: Lippincott-Raven.

Benoit, R. G., & Anderson, M. C. (2012). Opposing mechanisms support the voluntary forgetting of unwanted memories. *Neuron*, *76*, 450–460.

Bertsch, K., Hagemann, D., Naumann, E., Schächinger, H., & Schulz, A. (2012). Stability of heart rate variability indices reflecting parasympathetic activity. *Psychophysiology*, *49*, 672–682.

Braver, T. S., Paxton, J. L., Locke, H. S., & Barch, D. M. (2009). Flexible neural mechanisms of cognitive control within human prefrontal cortex. *Proceedings of the National Academy of Sciences, USA*, *106*, 7351–7356.

Brewin, C. R., Gregory, J. D., Lipton, M., & Burgess, N. (2010). Intrusive images in psychological disorders: Characteristics, neural mechanisms, and treatment implications. *Psychological Review*, *117*, 210–232.

Bulevich, J. B., Roediger, H. L., III, Balota, D. A., & Butler, A. C. (2006). Failures to find suppression of episodic memories in the think/no-think paradigm. *Memory & Cognition*, *34*, 1569–1577.

Depue, B. E., Burgess, G. C., Willcutt, E. G., Ruzic, L., & Banich, M. T. (2010). Inhibitory control of memory retrieval and motor processing associated with the right lateral prefrontal cortex: Evidence from deficits in individuals with ADHD. *Neuropsychologia*, *48*, 3909–3917.

Depue, B. E., Curran, T., & Banich, M. T. (2007). Prefrontal regions orchestrate suppression of emotional memories via a two-phase process. *Science*, *317*, 215–219.

Hansen, A. L., Johnsen, B. H., & Thayer, J. F. (2003). Vagal influence on working memory and attention. *International Journal of Psychophysiology*, *48*, 263–274.

Hertel, P. T., & Gerstle, M. (2003). Depressive deficits in forgetting. *Psychological Science*, *14*, 573–578.

Hertel, P. T., & Mahan, A. (2008). Depression-related differences in learning and forgetting responses to unrelated cues. *Acta Psychologica*, *127*, 636–644.

Hovland, A., Pallesen, S., Hammar, Å., Hansen, A., Thayer, J., Tarvainen, M., & Nordhus, I. (2012). The relationships among heart rate variability, executive functions, and clinical variables in patients with panic disorder. *International Journal of Psychophysiology*, *86*, 269–275.

Johnsen, B. H., Thayer, J. F., Laberg, J. C., Wormnes, B., Raadal, M., Skaret, E., . . . Berg, E. (2003). Attentional and physiological characteristics of patients with dental anxiety. *Journal of Anxiety Disorders*, *17*, 75–87.

Jurca, R., Church, T. S., Morss, G. M., Jordan, A. N., & Earnest, C. P. (2004). Eight weeks of moderate-intensity exercise training increases heart rate variability in sedentary postmenopausal women. *American Heart Journal*, *147*, 8–15.

Krypotos, A.-M., Jahfari, S., van Ast, V. A., Kindt, M., & Forstmann, B. U. (2011). Individual differences in heart rate variability predict the degree of slowing during response inhibition and initiation in the presence of emotional stimuli. *Frontiers of Psychology*, *2*, Article 278. Retrieved from http://www.frontiersin.org/Journal/10.3389/fpsyg.2011.00278/full

Lane, R. D., McRae, K., Reiman, E. M., Chen, K., Ahern, G. L., & Thayer, J. F. (2009). Neural correlates of heart rate variability during emotion. *NeuroImage*, *44*, 213–222.

Levy, B. J., & Anderson, M. C. (2002). Inhibitory processes and the control of memory retrieval. *Trends in Cognitive Sciences*, *6*, 299–305.

Levy, B. J., & Anderson, M. C. (2008). Individual differences in the suppression of unwanted memories: The executive deficit hypothesis. *Acta Psychologica*, *127*, 623–635.

Levy, B. J., & Anderson, M. C. (2012). Purging of memories from conscious awareness tracked in the human brain. *Journal of Neuroscience*, *32*, 16785–16794.

Levy, M. N. (1990). Autonomic interactions in cardiac control. *Annals of the New York Academy of Sciences*, *601*, 209–221.

Li, Z., Snieder, H., Su, S., Ding, X., Thayer, J. F., Trieber, F. A., & Wang, X. (2009). A longitudinal study in youth of heart rate variability at rest and in response to stress. *International Journal of Psychophysiology*, *73*, 212–217.

MacLeod, C., & Gorfein, D. (2007). *Inhibition in cognition*. Washington, DC: American Psychological Association.

Michael, T., Ehlers, A., Halligan, S. L., & Clark, D. M. (2005). Unwanted memories of assault: What intrusion characteristics are associated with PTSD? *Behaviour Research and Therapy*, *43*, 613–628.

Nugent, A. C., Bain, E. E., Thayer, J. F., Sollers, J. J., III, & Drevets, W. C. (2011). Heart rate variability during motor and cognitive tasks in females with major depressive disorder. *Psychiatry Research: Neuroimaging*, *191*, 1–8.

Paz-Alonso, P., Bunge, S. A., Anderson, M. C., & Ghetti, S. (2013). Strength of coupling within a mnemonic control network differentiates those who can and cannot suppress memory retrieval. *Journal of Neuroscience*, *33*, 5017–5026.

Paz-Alonso, P., Ghetti, S., Matlen, B., Anderson, M. C., & Bunge, S. (2009). Memory suppression is an active process that improves over childhood. *Frontiers in Human Neuroscience*, *3*, Article 24. Retrieved from http://www.frontiersin.org/Journal/10.3389/neuro.09.024.2009/full

Purdon, C. (2004). Empirical investigations of thought suppression in OCD. *Journal of Behaviour Therapy and Experimental Psychiatry*, *35*, 121–136.

Tang, Y.-Y., Ma, Y., Fan, Y., Feng, H., Wang, J., Feng, S., . . . Fan, M. (2009). Central and autonomic nervous system interaction is altered by short-term meditation. *Proceedings of the National Academy of Sciences, USA*, *106*, 8865–8870.

Tarvainen, M., Niskanen, J., Lipponen, J., Ranta-aho, P., & Karjalainen, P. (2009). Kubios HRV—A software for advanced heart rate variability analysis. In J. Vander Sloten, P. Verdonck, M. Nyssen, & J. Haueisen (Eds.), *IFMBE Proceedings, Vol. 22: 4th European Conference of the International Federation for Medical and Biological Engineering* (pp. 1022–1025). New York, NY: Springer. Retrieved from http://link.springer.com/chapter/10.1007/978-3-540-89208-3_243

Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. (1996). Heart rate variability: Standards of measurement, physiological interpretation and clinical use. *Circulation*, *93*, 1043–1065.

Thayer, J. F., Åhs, F., Fredrickson, M., Sollers, J. J., & Wager, T. D. (2012). A meta-analysis of heart rate variability and neuroimaging studies: Implications for heart rate variability as a marker of stress and health. *Neuroscience & Behavioral Reviews*, *36*, 747–756.

Thayer, J. F., & Lane, R. D. (2000). A model of neurovisceral integration in emotion regulation and dysregulation. *Journal of Affective Disorders*, *61*, 201–216.

Thayer, J. F., & Lane, R. D. (2009). Claude Bernard and the heart–brain connection: Further elaboration of a model of neurovisceral integration. *Neuroscience & Biobehavioral Reviews*, *33*, 81–88.

Wenzlaff, R. M., & Wegner, D. M. (2000). Thought suppression. *Annual Review of Psychology*, *51*, 59–91.