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Resting state heart rate variability and false memories

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ABSTRACT

Recent studies have shown higher resting-state vagally-mediated heart rate variability (vmHRV) to be related to greater memory retrieval. Research has not yet linked resting vmHRV with memory encoding *and* retrieval, as both are thought to play an important role in correctly distinguishing between true and false memories. The current study investigated this possible link in n = 71 undergraduate students. VmHRV was assessed during a 5-minute resting baseline period. Participants then completed the *Deese-Roediger-McDermott* (DRM) task, where they first viewed 6 word lists (12 words per list), and were later asked to identify previously shown words (true memories) and reject non-presented words. Results showed that participants with lower resting vmHRV were less able to discriminate true from false items. These data extend previous work on resting vmHRV and memory suggesting that resting vmHRV represents a psychophysiological pathway involved in both the proper encoding *and* retrieval of memories.

1. Introduction

When studying false memories, or memories that are inconsistent with actual experiences, both *memory encoding* and *memory retrieval* – the ability to find memory in long-term storage and bring it to mind – play an important role (Storbeck and Clore, 2005). Evidence suggests that executive brain function, defined as the proper or adaptive activity of executive brain regions such as the prefrontal cortex (PFC), is responsible for memory encoding and retrieval (Tulving et al., 1994; Blumenfeld and Ranganath, 2007) and thus, correctly distinguishing true from false memories (Storbeck and Clore, 2005). Resting-state[3] vagally-mediated heart rate variability (vmHRV) is widely recognized as a potential index of executive brain function, with higher resting vmHRV being related to better functioning of the aforementioned brain regions (Williams et al., 2019; Stenfors et al., 2016), in particular the PFC (Thayer et al., 2012). Here we sought to investigate if resting vmHRV plays a role in both memory *encoding* and memory *retrieval* in a false memory paradigm.

1.1. False memory

False memory (also referred to as memory errors or memory illusions) is known as the recall of inaccurate information of a particular event or stimulus (Roediger and McDermott, 1995). False memories can develop due to a variety of causes, including errors in storage and retrieval of information (Loftus, 2003). Memory is thought to consist of three general processes: *encoding*, *storage*, and *retrieval*. Memory *encoding* refers to the process of attending to a stimulus and bringing it into memory, *storage* consists of that stimulus being held in memory, and *retrieval* is the process of bringing that stimulus from storage back into

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[3] "Resting-state vmHRV" is simply referred to as "resting vmHRV" for the remainder of this report.

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working memory for conscious recall and usage (Tulving, 1995). Studies on memory tend to focus on accurate recall and memory biases; thus, false memory seems to be a less studied topic, especially in conjunction with psychophysiological correlates of memory. However, performing well on false memory paradigms involves accurate memory encoding, storage, and retrieval.

Importantly, both memory encoding and retrieval involve the activation and function of executive brain areas such as the PFC (Murty et al., 2010; Tulving et al., 1996; Storbeck and Clore, 2005; Badre and Wagner, 2007). The PFC allows individuals to organize behavior to effectively respond to environmental demands (Miller and Cohen, 2001). False memory paradigms have been associated with activity in such brain regions as the ventrolateral and anterior PFC (Schacter et al., 1997; Badre and Wagner, 2007). Research shows that one's ability to distinguish true from false memories is limited, and that there is individual variability in task performance, with executive function being a potential indicator of this performance (Otgaar and Smeets, 2010; Watson et al., 2005). As successful discrimination between true and false memories requires proper memory encoding and retrieval, proper functioning in brain areas such as the PFC is imperative to performance on false memory paradigms. Of note, studies have implicated sleep as another factor involved in memory consolidation (Payne et al., 2009; Newbury and Monaghan, 2019), and multiple studies have investigated HRV and its relation to sleep and sleep disorder (see Stein and Pu, 2012 for a review), identifying another potential pathway connecting HRV and potential development of false memories.

1.2. Resting vmHRV as it relates to executive brain function and cognitive control

The *Neurovisceral Integration Model* proposes that inhibitory processes are essential to autonomic nervous system (ANS), cognitive, behavioral and affective regulation (Thayer and Lane, 2000). The model proposes resting vmHRV – the temporal variation in beat-to-beat measurements in heart rate mediated by the vagus nerve – as a psychophysiological index of executive brain function and thus self-regulatory processes (e.g., cognitive control), in addition to overall health (for review, *see* Thayer et al., 2012; Thayer et al., 2009; Thayer and Sternberg, 2006, 2010). Of the two branches of the ANS, parasympathetic (PNS) activity slows heart rate, and sympathetic (SNS) activity accelerates heart rate, thus modulating HRV (Task Force, 1996). These PNS and SNS influences affect the heart through the stellate ganglia and most notably, the vagus nerve (the primary nerve of the PNS) through the sino-atrial node of the heart. PNS influences have been shown to be dominant in heart rate control and produces the fast, high frequency (order of magnitude of milliseconds) modulation which has been shown to reflect activity of the the vagus nerve (i.e., vmHRV; Levy, 1990; Kuo et al., 2005).

Neuroimaging studies support the notion that the reciprocal communication between executive and lower order brain areas such as the amygdala is reflected in HRV; at rest, vmHRV is related to executive brain regions such that greater activity in these regions is associated with greater vmHRV (for review, see Thayer et al., 2012; Lane et al., 2009; Nugent et al., 2011; Ahern et al., 2001). The vagus nerve is the vector for this influence, as it connects to the ventromedial PFC, right dorsolateral PFC, and orbitofrontal cortex, which is thought to allow for self-regulation of thoughts, emotions, and behavior (Chikazoe et al., 2007). Overall, this converging evidence connects vmHRV with the same brain regions that influence cognitive control (see Thayer et al., 2009; Thayer et al., 2012, *for reviews*), including control over memory (Gillie et al., 2014).

1.3. HRV and memory control

Evidence from neuroimaging studies provides a neurophysiological basis for the potential link between resting vmHRV and memory processes, as similar brain regions are responsible for the regulation of both. Behavioral studies also support this notion; in one study of participants who were instructed to learn and then forget pairings of words (via a standard think-no-think task), those with higher resting vmHRV successfully suppressed memories for words they were instructed to forget (Gillie et al., 2014). Additionally, existing literature points to a relation between HRV and memory consolidation during sleep (Whitehurst et al., 2016). If higher resting vmHRV is related to better executive functioning, cognitive control, and memory retrieval, and the discrimination between true and false memories involve memory encoding and retrieval that rely on executive processes, those with greater resting vmHRV should perform better in a false memory paradigm. However, no study has yet investigated the relation of resting vmHRV and the ability to discriminate between true and false memories.

1.4. Present study

In the present study, we used a popular false memory paradigm in which participants studied a number of word lists, and later indicated whether a word was or was not previously presented. We expected that those with higher resting vmHRV would better identify previously shown words or true memories, correctly reject lure or category words not previously presented (i.e., false memories), and better discriminate between the two. Specifically, we expected that resting vmHRV would not only predict the ability to retrieve (and in some instances control) memories (Gillie et al., 2014), but also would be associated with the ability to properly encode memories and discriminate between true and false ones.

2. Methods & materials

2.1. Participants

Data from n = 71 undergraduate students (n = 40 females, 18.8 ± 1.4 years; age range: 18–26 years) were included in the study. Participants were recruited through the Research Experience Program (REP) at a large Midwestern university. Student participation was voluntary, and participation in this study was one of several options available for obtaining course credit. The current study had IRB approval prior to recruitment of participants. We asked all participants not to smoke, undergo vigorous physical activity, or drink caffeine during the 6 h prior to the experiment.

2.2. Procedure

Following written informed consent, the experimenter collected the participant's age, gender, and ethnicity. Subjects then completed a 5-min resting-baseline in a seated position while spontaneously breathing. Participants were instructed to relax but not to fall asleep. Following this period, participants completed the false memory task, and were then debriefed and dismissed from the study.

2.3. The false memory paradigm

We used the *Deese-Roediger-McDermott* (DRM) paradigm for the assessment of false memory performance (Deese, 1959; Roediger and McDermott, 1995). The typical presentation of this task is to show lists of words, asking participants to recall as many words as they can remember after each word list. After recalling several word lists, participants are prompted to distinguish between previously shown words and novel (lure) words. Falsely identifying a lure word as a previously shown word is interpreted as a false memory. In line with this traditional presentation of the DRM paradigm, participants in this study were shown six word lists (consisting of 12 words per list). After each word list, participants were asked to type in as many words as they remembered from that list. Following the six word lists, participants completed

Table 1
Word lists, categories, and filler words used for the DRM paradigm.

Category (Lure) Words:

Words Lists (12 words per list)	*Anger*	*Chair*	*City*	*Cold*	*Doctor*	*Cup*
W1	mad	table	town	hot	nurse	mug
W2	fight	cushion	metropolis	freeze	patient	goblet
W3	hate	legs	state	warm	lawyer	tea
W4	rage	seat	capital	winter	medicine	measuring
W5	temper	couch	street	ice	health	coaster
W6	fear	sit	crowd	snow	sick	saucer
W7	ire	recliner	country	chill	dentist	handle
W8	wrath	sofa	New York	heat	physician	coffee
W9	happy	wood	village	weather	ill	straw
W10	fury	desk	subway	frigid	hospital	lid
W11	hatred	swivel	big	air	office	soup
W12	mean	stool	Chicago	wet	stethoscope	stein

Filler (unrelated) Words Presented at Recognition Phase:

mountain	smoke	hill	water	smooth	bed	fast	nose
river	soft	cigarette	hard	web	sour	garbage	door
rough	spider	valley	stream	bumpy	rest	stop	breathe
sleep	sweet	puff	light	insect	candy	waste	glass
slow	trash	climb	lake	road	awake	lethargic	sniff
smell	window	blaze	pillow	bug	sugar	can	pane

Note: the above table shows the six categories (anger, chair, etc.) from which word lists were created. At the recognition phase following the presentation of all six word lists, participants were responsible for identifying and distinguishing between true, false (category words not previously shown), and filler words (unrelated words not previously shown). Three words from each category were included in the recognition phase (in the table, words included at the recognition phase are shaded gray). The six category or lure words (words directly related to the word lists and corresponding categories associated with the presentation stage) were also shown at this time, and were considered false memories.

the recognition phase, where they were prompted to identify previously shown words amongst new, novel words. Participants were shown a total of 72 words, with 18 of the words having been previously presented (true words) and 48 words unrelated to previously shown topic lists. Finally, six words were considered lure or false memory words; these words represented the category word of the previously shown word lists. For example, participants were presented with words related to the category of "bed" (e.g., *sleep*, *nighttime*). These category words were randomized and later shown to the participant, however, the lure (category) word *bed* was also shown. If the participant reported that they saw *sleep*, this would be considered a true memory. If the participant reported that they saw *bed*, this would serve as a false memory, as that word was not shown in the actual word list.

The outcome variables reported include *hit rate*: defined as the proportion of true words participants correctly identified as true with higher proportions reflecting better identification of true memories; *false alarm rate*: defined as the proportion of lure or false words incorrectly identified as true words with lower proportions reflecting better rejection of false memories; *D-prime* (D'): was calculated in accordance with signal detection theory and is defined as the normalized distance between the participants true and false memory rates, with greater positive values reflecting better discrimination between true and false memories ($\mathbf{D'(1)}$ = z (hit rate) – z (false alarm rate); Macmillan, 1993). Higher D' values reflected a greater hit rate relative to false alarm rate. D' values were also calculated using the irrelevant words to show participants' performance on discriminating between both true and lure words from filler words ($\mathbf{D'(2)}$ = z(hit rate) – z(filler rate); $\mathbf{D'(3)}$ = z(false alarm rate) – z(filler rate)). For the calculation of each D', in the event that a participant scored a proportion of 0 or 1 for either hit, false alarm, or filler rates, those rates were slightly adjusted to 0.001 and 0.999 respectively as a normalized value of 0 or 1 approaches infinity, thus resulting in an error for the calculation of D'. Table 1 provides an overview of the word lists, categories, and filler words used for the DRM paradigm.

2.4. Vagally-mediated heart rate variability (vmHRV)

During the 5-minute resting baseline, continuous inter-beat-intervals (IBIs; time in milliseconds between heart beats) were assessed at a sampling rate of 1000 Hz via a 2-lead portable heart rate monitor (FirstBeat BodyGuard 2, Firstbeat Technologies Ltd., Jyväskylä, Finland). Electrodes were placed under the right clavicle and the last left ribcage. IBIs were collected from the device and imported directly into Kubios HRV Analysis (ver. 2.2) software (Tarvainen et al., 2009). Artifact correction was completed by visually inspecting and removing artifacts using appropriate correction levels in Kubios. Our analysis focuses on the root mean square of the successive differences (RMSSD) between IBIs, a measure that is considered to reflect vagally-mediated HRV (Task Force, 1996), as vagally mediated parasympathetic activity is of interest in this study. All HRV measures (ms units) were log transformed to normalize the data for analysis. Task Force recommendations were followed in all procedures (Task Force, 1996).

Table 2
Sample characteristics.

n = 71	Age	BMI	HF Peak	Resting vmHRV	Hit rate	FA Rate	Filler rate	D′ (1)	D′ (2)	D′ (3)
Mean –	18.82	22.27	0.27	3.68	54%	55%	40%	−0.08	0.54	0.62
SD –	1.36	2.62	0.05	0.49	31%	11%	10%	0.60	1.31	1.41

Note: This table gives means and standard deviations (SD) of baseline physiological and DRM performance variables. Age: measured in years; BMI: body mass index (kg/m^2); HF peak: index of respiration; vmHRV: resting vagally mediated heart rate variability indexed by the natural log (ln) of the root mean of the squared successive differences (lnRMSSD); hit rate: the proportion (displayed as percentage (%) in table) of true memories correctly identified as true; false alarm (FA) rate: the proportion (displayed as percentage (%) in table) of false memories (lure words) incorrectly identified as true memories; filler rate: the proportion (displayed as percentage (%) in table) of filler words (irrelevant words) incorrectly identified as true memories; D′(1): this d-prime reflects the normalized distance between hit and false alarm rates; D′(2): this d-prime reflects the normalized distance between hit and filler rates; D′(3): this d-prime reflects the normalized distance between false alarm and filler rate (see Methods for details on rates and D′ values).

Table 3
Correlations between variables.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
1. Resting vmHRV	–						
2. FA rate	**−.258***	–					
3. Hit rate	−.144	**.846****	–				
4. Filler rate	−.031	**−.702****	**−.733****	–			
5. D′(1)	**.351****	**−.417****	.096	.072	–		
6. D′(2)	−.079	**.866****	**.983****	**−.787****	.056		
7. D′(3)	−.213	**.982****	**.874****	**−.763****	**−.371****	**.906****	–

Note: this table shows a correlation coefficient matrix between variables. VmHRV is meant to represent resting vagally mediated heart rate variability indexed by the natural log (ln) of the root mean of the squared successive differences (lnRMSSD). Hit rate: the proportion of true memories correctly identified as true; false alarm (FA) rate: the proportion of false memories (lure words) incorrectly identified as true memories; filler rate: the proportion of filler words (irrelevant words) incorrectly identified as true memories; D′(1): this d-prime reflects the normalized distance between hit and false alarm rates; D′(2): this d-prime reflects the normalized distance between hit and filler rates; D′(3): this d-prime reflects the normalized distance between false alarm and filler rate (see Methods for details on rates and D′ values). Bold signifies a statistically significant result.

* $p < .05$.

** $p < .01$.

2.5. Statistical analyses

All statistical tests were conducted using SPSS (ver. 22, IBM Chicago, IL, USA). All tests involving hit, false alarm, and filler rates were conducted using unadjusted values. All D′ values (D′(1), D′(2), and D′(3); see above for details) were calculated using adjusted normalized rates as previously described.

First, zero-order correlations were calculated to investigate the relationship between resting vmHRV and indices of performance on the DRM paradigm, including hit rates, false alarm rates, filler rates, and the three D′ variables. Hierarchical multiple regression analyses were then used to examine the association between resting vmHRV and each performance index while controlling for potential confounds. Ethnicity (Hill et al., 2015), gender (Koenig and Thayer, 2016), age (Choi et al., 2006), and BMI (Koenig et al., 2014) have all been associated with resting vmHRV and thus, were considered as covariates in regression analyses. Model 1 included BMI (continuous, in kg/m^2), age (continuous, in years), gender (factorial, coded as 1 = male, 2 = female), and ethnicity (factorial, coded as 1 = European Americans, 2 = other) as predictors of performance on the DRM task. Model 2 added resting vmHRV and respiratory rate (HF peak; Thayer et al., 2002) as predictors. Partial correlation coefficients between independent variables and dependent variables are reported to indicate the strength of the relationship while controlling for the other variables. All tests were two-tailed and were analyzed using a set level of significance of $p < .05$.

3. Results

Table 2 gives means and standard deviations for demographic variables, resting vmHRV, and performance on the task for the current sample (n = 71). The overall hit rate was 54%, while the overall false alarm rate was 55%. Filler rate – the percentage of filler words (irrelevant words) incorrectly identified as true memories – was 40%. D′, D′2, and D′3 were −0.08, 0.54, and 0.62 respectively.

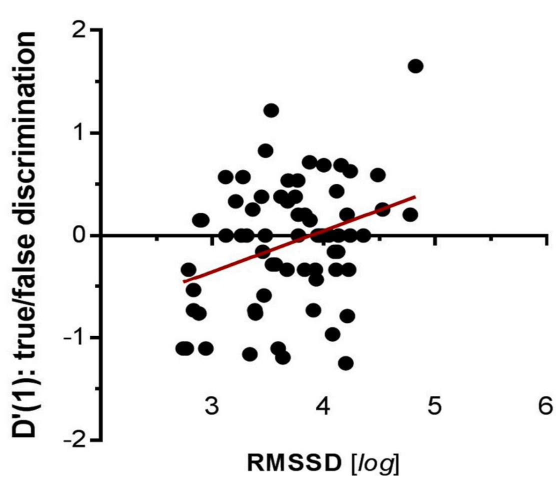

Fig. 1. Scatterplot of Resting vmHRV and D′(1).
Note: this figure shows a significant positive relationship between resting vmHRV, indexed by the natural log (ln) root mean of the squared successive differences (lnRMSSD) and D′ (r = .351, $p = .002$).

Table 3 presents the correlations between all variables. A negative correlation is present between false alarm rate and resting vmHRV (r = −.258, $p < .05$) meaning that those with lower vmHRV produced more false memories. Moreover, there was a significant correlation between resting vmHRV and false alarm rates such that those with lower resting vmHRV showed both higher false alarm rates and poorer discrimination between true and false memory-words on the task. Fig. 1 depicts the positive relationship between resting vmHRV and D′(1) (r = .351, p = .002). There was no significant relationship between resting vmHRV and

Table 4
Summary of hierarchical regression analysis for variables predicting performance on the DRM paradigm.

	Hit rate		FA rate		Filler rate		D′(1)		D′(2)		D′(3)	
Step	1	2	1	2	1	2	1	2	1	2	1	2
Age	−0.150	−.153	−.230	−.217	.096	.085	.169	.137	−.149	−.149	−.210	−.196
Ethnicity	−.148	−.132	−.081	−0.035	−.042	−.046	−.114	−.193	−.119	−.109	−.063	−.025
Gender	.027	.004	.081	.071	.049	.035	−.092	−.100	.013	.002	.052	.043
BMI	−.114	−.116	−.128	−.157	**.265***	**.268***	.016	.069	−.138	−.137	−0.136	−.159
HF peak		.087		.000		.062		.102		.041		−.002
Resting vmHRV		−.107		**−.251***		.006		**.367****		−.055		−.208
Constant	1.58	1.70	1.85	2.40	0.01	−0.03	−1.16	−2.97	5.12	5.40	6.29	8.37
R^2	0.059	0.081	0.090	0.149	0.080	0.083	0.059	0.170	0.057	0.062	0.075	0.116

Note: This table shows partial r coefficients with associated significance levels at each step in the regression model. Age is measured in years, ethnicity is coded as 1 (White) and 2 (minority); gender is coded as 1 (men) and 2 (women); BMI: body mass index (kg/m^2); HF peak: index of respiration; resting vmHRV: resting vagally mediated heart rate variability indexed by the natural log (ln) of the root mean of the squared successive differences (lnRMSSD). hit rate: the proportion of true memories correctly identified as true; false alarm (FA) rate: the proportion of false memories (lure words) incorrectly identified as true memories; filler rate: the proportion of filler words (irrelevant words) incorrectly identified as true memories; D′(1): this d-prime reflects the normalized distance between hit and false alarm rates; D′(2): this d-prime reflects the normalized distance between hit and filler rates; D′(3): this d-prime reflects the normalized distance between false alarm and filler rate (see Methods for details on rates and D′ values). Bold signifies a statistically significant result.

* *p < .05.*

** *p < .01.*

hit rates (r = −.144, *p* = .232), filler rates (r = −.031, *p* = .801), D′(2) (r = −.079, *p* = .515), and D′(3) (r = −.213, *p* = .075).

Multiple hierarchical regression models showed that, after controlling for, age, ethnicity, sex, BMI, and HF peak (respiration) values, resting vmHRV remained significantly associated with false alarm rates ($r_{partial} = -.251$, *p* = *.042*) and D′(1) ($r_{partial} = .367$, *p* = *.002*), but no significant relationship between resting vmHRV and hit rates, filler rates, D′(2), or D′(3) (each *p* > .05; see Table 4 for a summary of regression models for all indices of performance).

4. Discussion

The current study investigated how resting vmHRV is related to the ability to discriminate between true and false memories. We showed that lower resting vmHRV is associated with a higher rate of incorrectly identifying lure words (i.e., false memories) as true words. No significant relationship was found between resting vmHRV and hit rates. Importantly, those with lower resting vmHRV displayed impaired discrimination between true and false memories (i.e., difficulties in maximizing hit rate while minimizing false alarm rate – lower D′(1) values). No significant relationship was found between resting vmHRV and the other D′ values, suggesting that the relationship between resting vmHRV and performance was specific to true words and associated category words (i.e., lure words). Thus, perhaps this relationship is especially relevant to the memory specificity of related concepts (in this case, related words) in comparison to filler words. Overall, this investigation lends support to prior research (Thayer and Lane, 2000; Thayer et al., 2009; Gillie et al., 2014), suggesting that resting vmHRV is indeed an index of cognitive control particularly as it relates to memory retrieval and extending this idea into the domain of memory encoding.

Previous research has found that individuals with higher resting vmHRV tend to perform better on cognitive control tasks relative to those with lower resting vmHRV (Thayer and Brosschot, 2005; Thayer et al., 2000; Thayer and Lane, 2000; Hansen et al., 2003; Gillie et al., 2014). Specifically, increased cognitive control over memory - which is related to better performance on tasks assessing inhibitory control, working memory, memory retrieval, sustained attention, and other tasks associated with memory- is associated with higher resting vmHRV (Krypotos et al., 2011; Hansen et al., 2003; Johnsen et al., 2003; Hovland et al., 2012; Gillie et al., 2014). As it pertains to false memory, the activation-monitoring framework proposes that false memory errors occur at both memory encoding and retrieval stages (Roediger et al., 2001). During memory encoding, the semantically related items on the task might be activated in memory. When the subject then performs retrieval, the activated words come to memory as well, and are misattributed to being in the original list (Storbeck and Clore, 2005). Encoding memories by focusing on the words individually, as opposed to encoding memories by relating the words to other objects in memory has been found to reduce false memory recall (Arndt and Reder, 2003). Thus, memory encoding as well as memory retrieval are important processes in successful completion of the DRM paradigm (Gallo, 2010). Overall, both previous research and the current study provide converging evidence of a link between resting vmHRV and memory processes, however the current investigation is the first to suggest a direct link between resting vmHRV and both memory retrieval *and* encoding.

In sum, performance on the DRM paradigm hinges on both sufficient memory encoding and memory retrieval via adequate activation of executive brain regions (Schacter et al., 1997; Badre and Wagner, 2007). The present findings suggest that individual differences in resting vmHRV may predict the degree to which one has efficient and specific memory encoding and retrieval processing. Whereas the present results are in a young, healthy sample, additional studies in older adult samples are needed to examine the generalizability of these findings.

4.1. Implications

These findings provide evidence that in tasks where individuals are required to distinguish between true and false memories (e.g. in eyewitness testimony), resting vmHRV can potentially serve as an index of such memory abilities. This is important as not only can veracity of memory affect proceedings such as eyewitness testimony, but additionally there is evidence that false memories can affect individuals' future behavior (Loftus, 1996; Loftus, 2003; Geraerts et al., 2008). For example, Loftus and Pickrell (1995) were able to show that individuals could develop a false autobiographical memory of being "lost in a mall" after suggestion by interviewers. In addition, Geraerts et al. (2008) designed a study in which participants were suggested the false memory of having previously gotten sick from eating an egg salad sandwich. The researchers found persistent changes in behavior such that due to this believe at 4 months post induction, participants showed a reduction in eating of egg salad sandwiches. While this is a relatively benign form of false memory, one could imagine that other memory errors could lead to more significant variations in behavior with stronger consequences. Low vmHRV seems to be a potential indicator of individuals prone to these memory errors.

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