

The influence of autonomic arousal and semantic relatedness on memory for emotional words

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Abstract

Increased memory for emotional stimuli is a well-documented phenomenon. Emotional arousal during the encoding of a stimulus is one mediator of this memory enhancement. Other variables such as semantic relatedness also play a role in the enhanced memory for emotional stimuli, especially for verbal stimuli. Research has not addressed the contributions of emotional arousal, indexed by self-report and autonomic measures, and semantic relatedness on memory performance. Twenty young adults (10 women) were presented neutral-unrelated words, school-related words, moderately arousing emotional words, and highly arousing taboo words while heart rate and skin conductance were measured. Memory was tested with free recall and recognition tests. Results showed that taboo words, which were both semantically related and high arousal were remembered best. School-related words, which were high on semantic relatedness but low on arousal, were remembered better than the moderately arousing emotional words and semantically unrelated neutral words. Psychophysiological responses showed that within the moderately arousing emotional and neutral word groups, those words eliciting greater autonomic activity were better remembered than words that did not elicit such activity. These results demonstrate additive effects of semantic relatedness and emotional arousal on memory. Relatedness confers an advantage to memory (as in the school-words), but the combination of relatedness and arousal (as in the taboo words) results in the best memory performance.

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1. Introduction

Emotional stimuli are better remembered than neutral stimuli. This pattern holds for pictures (Bradley et al., 1992), words (Kleinsmith and Kaplan, 1963), sounds (Bradley and Lang, 2000), and autobiographical experiences (Rubin and Schulkind, 1997). The arousal induced by the to-be-remembered stimuli is a strong determinant of subsequent memory performance (Bradley et al., 1992; Kensinger and Corkin, 2004). The neurobiology of this phenomenon has been the focus of much research, and it has been demonstrated that the amygdala plays an important role in the enhancement of emotional memory (Buchanan and Adolphs, 2004; Cahill,

2000; Hamann, 2001). Amygdala activity during the encoding of emotionally salient stimuli is predictive of subsequent memory (Canli et al., 2000), and damage to the amygdala abolishes the emotional enhancement of memory (Adolphs et al., 1997).

Psychophysiological measures have been used to index various processes associated with memory. Autonomic measures such as heart rate (HR), skin conductance responses (SCR), and pupil dilation all show covariation with memory processes (Jennings and Hall, 1980; Kahneman et al., 1969). This work has alternately shown that HR acceleration or deceleration is associated with better memory, depending upon experimental contingencies (Jennings and Hall, 1980). The autonomic response to emotional stimuli may be more reflective of subsequent memory than responses to neutral stimuli. The orienting response to emotional stimuli—characterized by HR deceleration, SCR increase, and pupil dilation—may

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act to enhance the encoding of incoming stimuli (Sokolov, 1963). Bradley et al. (1992) have shown that SCRs to emotionally arousing stimuli showed a strong correspondence with subsequent memory of those stimuli, and both measures—SCR and memory performance—were highly predicted by arousal ratings.

The mnemonic advantage of emotional words over neutral words could arise through a separate mechanism from an arousal response, however (Maratos et al., 2000; Talmi and Moscovitch, 2004). Compared to unrelated neutral words, emotional words often show a high degree of semantic relatedness. Words related to emotion tend to be associated with one another, while neutral comparison words may be unrelated. This semantic relatedness, known as “semantic cohesion,” increases memory performance by reducing the search parameters in retrieval (Tulving and Pearlstone, 1966). Studies that have controlled for semantic relatedness and subjective emotional ratings have shown that semantically related words are as well remembered as emotional words (Maratos et al., 2000; Talmi and Moscovitch, 2004).

It is unclear to what degree emotional arousal influences memory for emotional material over and above the effects of semantic cohesion. The current study set out to examine autonomic responses to, and memory for, words that vary on the dimensions of arousal and semantic relatedness. We examined memory for neutral unrelated words and three semantically related word groups (moderately arousing unpleasant emotional words, school-related neutral words, and highly arousing taboo words). We hypothesized that within semantically related word groups, increasing arousal would be associated with enhanced memory and that heart rate and skin conductance responses to individual words may predict subsequent memory performance.

2. Methods

2.1. Participants

Twenty young adults (10 female, mean age = 19.1 ± 0.85) participated in the study for class credit. All participants signed a consent form approved by the University of Iowa Institutional Review board before starting the experiment.

2.2. Materials

A list of 80 words was compiled, including 20 unpleasant emotional words, 20 words related to school/university, 20 sexually explicit taboo words, and an unrelated set of 20 emotionally neutral/unrelated words. The unpleasant emotional words and neutral/unrelated words were drawn from the Affective Norms for English Words database (Bradley and Lang, 1999). The unpleasant words were chosen because they were low on pleasantness (valence) and relatively high on arousal (mean normative rating of valence = 2.0; arousal = 6.1, on scales of 1–9). The neutral/unrelated words were chosen to be in the middle range on pleasantness ($M = 5.5$) and low on arousal ($M = 4.1$). School-related words were compiled from a

list used in previous research (Dillon et al., 2003). Taboo words were sexually explicit words including profanities (LaBar and Phelps, 1998). Since most of the school-related and taboo words are not included in traditional counts of word frequency (Francis and Kucera, 1982), estimates of frequency were computed using the Alta Vista internet search engine (Blair et al., 2002). Each word was entered into the search function of Alta Vista; the number of hits returned was recorded as the frequency estimate for each word. Results of this analysis showed that there was not a significant difference in word frequency across the categories, $F(3, 76) = 1.7$, $p = 0.174$. Mean frequencies for each category: neutral/unrelated: 4,617,834 ± 686,574 (SEM); unpleasant: 2,935,443 ± 320,820; school: 6,353,840 ± 1,916,720; taboo: 6,242,050 ± 1,275,424 (we note that the large number of sexually explicit Internet websites may have overestimated the frequency of the taboo words).

The semantic relatedness of the words was estimated by a preliminary experiment in a separate set of participants. Six participants (3 male/3 female; mean age = 26) rated each word on a scale of 0–4 for inclusion in each of the following categories: school/university, generally unpleasant, sexually explicit/taboo, and neutral/unrelated (words that did not fit within the other 3 categories). Inter-rater reliability for each a priori word category was measured using Cronbach's alpha. Reliability for all word categories: school-related = 0.993; unpleasant = 0.956; taboo = 0.982; neutral/unrelated = 0.885. These data demonstrate high reliability for the classification of the word categories (although the neutral/unrelated words were somewhat lower than the other categories).

2.3. Psychophysiological measures

Heart rate was measured using 2 electrocardiograph electrodes, one placed on the right side of the neck and the other on the left side of the torso 2 cm below the rib cage. Skin conductance was measured using 2 Ag–AgCl electrodes placed on the thenar and hypothenar surfaces of the left palm. Signals were recorded at 500 Hz using a Biopac (Biopac Systems, Santa Barbara, CA) MP150 system including amplifiers for ECG and SCR collection. Heart beats were detected by recording the sample at which each normal R wave occurred. The R waves were identified offline using the ecgwave program (Jane et al., 1997) from the PhysioToolkit (Moody et al., 2001), as described in (Etzel et al., 2004). The time at which each word was presented was also identified and recorded.

2.4. Procedure

Each participant viewed a randomly selected set of 10 neutral/unrelated, 10 unpleasant, 10 school-related, and 10 taboo words drawn from the total list of 80 words. The remaining 40 words were used as foils in the recognition memory test (see description below). Two buffer words were presented at the beginning and end of the stimulus presentation to control for primacy and recency effects. These buffer words were not included in subsequent analyses. Each word was

presented for 4 s with an inter-stimulus interval (blank screen) shown for an interval randomly ranging between 3000 and 3950 ms. Words were presented in 40-point white Arial font on a black background at the center of a 19-in. monitor. Stimuli were presented via Presentation software (Neurobehavioral Systems, Albany, CA). Participants were asked to attend to the words and try to remember as many as possible.

Immediately after stimulus presentation, participants completed a free recall test. After a one-hour distractor task, participants completed a delayed free recall test. Participants then completed a recognition memory test; they viewed all 80 words (40 they had seen previously, and 40 new words) and were asked to respond ‘yes’ or ‘no’ as to whether they remembered seeing the word before. After responding to the recognition question, the participant rated each word on 5-point scales of pleasantness (1=unpleasant; 5=very pleasant) and arousal (1=low arousal; 5=high arousal).

2.5. Data management and analysis

Free recall data were scored as the number of words correctly recalled within each category at immediate and delayed time intervals (which were combined for analysis due to similar patterns of results). Recognition memory data were reduced by computing signal detection indices of performance. The number of hits (correct recognition of previously presented words) and false alarms (incorrect recognition of new words) were computed along with an index of discriminability (d' ; (Snodgrass and Corwin, 1988). Analyses of memory results, SCRs, and ratings of stimuli used a 2 Sex \times 4 Category (Neutral/unrelated, School-Related, Unpleasant, Taboo) repeated measures multivariate analysis of variance. All follow-up contrasts were corrected for inflation of Type I error rate using the Bonferroni procedure. Sex differences were assessed because previous research has suggested that men rate sexual stimuli as more arousing than women (Murnen and Stockton, 1997) and men and women differ in their memory of emotional (Cahill et al., 2004; Canli et al., 2002) and sexually explicit materials (Geer and McGlone, 1990). There were no main effects of sex, but sex did interact with arousal ratings and SCRs. Discussion of gender effects for these factors is included in the results.

For skin conductance, the maximum change recorded between 0.9 and 4 s after stimulus onset was recorded as the response measure (the criterion for the smallest scorable SCR was set at 0.01 μ S).

The mean heart rate change in consecutive 500 ms bins for five seconds following the presentation of each word was used as the measure of cardiovascular activity. Calculations were performed offline using programs written in R statistical software (R Development Core Team, 2005). The mean heart rate in the 500 ms bin immediately preceding the onset of the word stimulus was used as the baseline; the mean heart rate in each of the bins following the stimulus was subtracted from this baseline to obtain mean heart rate change. The mean heart rate in each bin was calculated by taking the weighted mean of

all RR intervals overlapping the bin after the RR intervals had been converted to heart rate in beats/minute.¹

The pattern of heart rate changes in response to the stimuli was plotted using lowess curves to summarize responses within and between subjects. Lowess curves were calculated using the R *lowess* function (Cleveland, 1981). Lowess (also called loess) calculates a locally-weighted least-squares line through the data. The resulting line is often similar to the mean but less sensitive to outliers and more appropriate for data sets with unequal variances at each time point (Diggle, 2002). Statistical significance of the lowess curves describing heart rate responses over time was assessed by calculating null bands using permutation testing² for each curve. Null bands indicate where the lowess curves describing the data fall under the null hypothesis (no relationship between the heart rate changes and type of stimulus or recall (Buja and Rolke, submitted for publication)). If the true lowess line falls outside its null bands, the line is considered unlikely to have occurred by chance. The null bands for each curve were set at the 95% and 5% quantile lines resulting from lowess curves describing each of 1500 permutations of the data set. Each permuted data set was created by randomly reassigning the label of interest (word category, bin number, or recall accuracy) within each subject then calculating lowess curves in the same manner as for the true data.

3. Results

3.1. Valence and arousal ratings

Table 1 shows ratings of valence and arousal by gender. Data from one male participant are missing from these analyses due to computer malfunction. As expected, there was a significant main effect of word category on valence, $F(3, 15)=56.0$, $p<0.0001$, $\eta^2=0.92$, with the unpleasant words rated as lower valence than the other word categories. Arousal ratings were also significantly different across word categories, $F(3, 15)=18.9$, $p<0.0001$, $\eta^2=0.79$, with the unpleasant and taboo words rated as more arousing than the other categories. Men and women rated the arousal of the words differently, as evidenced by a significant Gender by Category interaction, $F(3, 15)=5.9$, $p=0.007$, $\eta^2=0.54$, specifically, the men rated the taboo words as more arousing than the women.

¹ At 500 Hz, 500 ms bins are 250 samples long. The first and last sample number of each bin was identified, as well as that of the R wave immediately preceding the bin, all R waves in the bin, and the first R wave after the bin. All RR intervals overlapping the bin were converted to heart rate (beats/minute). The mean heart rate in the bin was calculated by taking the average of the heart rate at each of the 250 samples contained in the bin.

² The variance structure of these data make parametric statistical testing inappropriate: rather than a single measure of heart rate change for each stimulus presentation we used the mean heart rate change for each of ten time points following the stimulus. Measurements for each stimulus should be more correlated than measures for other stimuli within the same subject, and measurements within each subject should be correlated (see Edgington (1995), Ludbrook and Dudley (1998).

Table 1
Ratings of valence and arousal across word categories and gender

Category	Men		Women	
	Mean	SEM	Mean	SEM
Neutral				
Valence	3.0	0.15	3.0	0.14
Arousal	1.3	0.19	2.0	0.18
School				
Valence	3.0	0.16	3.0	0.15
Arousal	1.5	0.2	2.2	0.22
Unpleasant				
Valence	1.3	0.12	1.4	0.12
Arousal	2.6	0.36	2.5	0.34
Taboo				
Valence	2.7	0.19	2.1	0.18
Arousal	3.5	0.27	2.7	0.26

3.2. Free recall

Fig. 1 shows immediate and delayed free recall data. There was a significant main effect of delay on free recall performance, $F(1, 19)=14$, $p<0.01$, $\eta^2=0.4$, with significant forgetting between the immediate and delayed testing interval. The delay factor did not, however, interact with category or gender, $F_s<1$, so the data were collapsed over the delay factor. There was a significant main effect for category on both immediate and delayed free recall, $F(3, 16)>26$, $p_s<0.0001$, $\eta^2>0.82$. Participants recalled taboo words significantly better than all other categories ($p_s<0.001$, Bonferroni corrected). School words were remembered significantly better than neutral/unrelated words ($p<0.01$), but not better than unpleasant words ($p=0.1$). Recall of unpleasant words and neutral/unrelated words did not differ ($p>0.4$). These effects were similar for both immediate and delayed free recall. These results show that emotional arousal and semantic cohesion each contribute to memory performance. Based on memory performance of the school words compared to the unpleasant words, it appears that semantic cohesion confers more of a memory advantage than does emotional arousal. Additionally, the effects of semantic cohesion and

Table 2
Recognition of words across categories

Category	Hit rate		False alarm rate		d'	
	Mean	SEM	Mean	SEM	Mean	SEM
Neutral	0.78 ^a	0.04	0.21 ^a	0.04	1.8 ^a	0.26
School	0.86	0.02	0.15	0.03	2.4	0.21
Unpleasant	0.78 ^a	0.03	0.25 ^a	0.03	1.6 ^{a,b}	0.22
Taboo	0.91	0.02	0.10	0.02	2.9	0.20

^a Denotes significant difference from taboo words (Bonferroni corrected).
^b Denotes trend toward significant difference from school words ($p=0.076$).

arousal were additive, in that taboo words were remembered best of all.

3.3. Recognition

Table 2 shows hit rates, false alarm rates, and discriminability across all word categories. (One male participant's data were missing due to equipment malfunction.) There was a significant main effect for word category on hit rate, $F(3, 15)=5.9$, $p=0.007$, $\eta^2>0.54$. Planned follow-up tests showed higher hit rates for the taboo words compared to the neutral/unrelated and unpleasant words ($p<0.05$), but not higher than the school-related words. False alarm rates were significantly different among the word categories, $F(3, 15)=6.3$, $p=0.006$, $\eta^2>0.55$; higher false alarm rates were found for unpleasant words compared to school-related and taboo words ($p<0.05$), but not compared to neutral/unrelated words. Participants also produced more false alarms to neutral/unrelated compared to taboo words ($p<0.05$). There were category differences in discriminability (d') of the old versus new stimuli, $F(3, 15)=7.0$, $p=0.004$, $\eta^2=0.58$. As expected from the aforementioned hit rate and false alarm results, d' was significantly higher for the taboo words compared to the unpleasant and neutral/unrelated words ($p_s<0.05$). There was a trend toward a higher discriminability of school-related words compared to unpleasant words ($p=0.09$). As in free recall performance, there is better memory for taboo and school words compared to the other word groups.

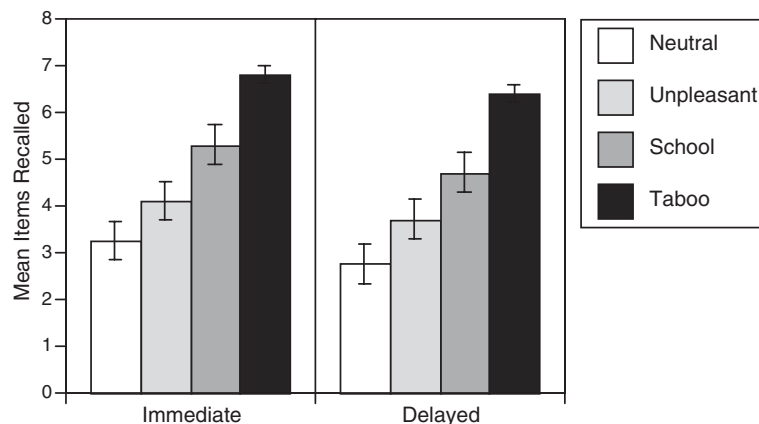


Fig. 1. Immediate and delayed free recall performance across word categories. Error bars show standard error of the mean.

3.4. Skin conductance responses

Table 3 shows SCRs to words of each category. There was a significant effect of word category on SCRs, $F(3, 16)=3.4$, $p=0.04$, $\eta^2>0.39$, with marginally greater responses to taboo words than neutral/unrelated words ($p=0.054$). There was a trend toward a Sex by Category interaction, $F(3, 16)=2.6$, $p=0.09$, $\eta^2=0.32$, with men showing slightly greater responses to the taboo words than women. These results demonstrate that the taboo words elicited greater physiological arousal than did the other word categories.

3.5. SCRs and memory performance

SCRs to individual words may serve as an index of subsequent memory for that word. To assess this possibility, we examined the SCRs to words that were later recalled versus forgotten in immediate and delayed free recall test using effect size analysis due to the small sample size and high variability of SCR data (Cohen, 1988). Results for *immediate* free recall showed that SCRs to the correctly recalled taboo words ($M=0.55 \mu\text{S}$) were larger than to those that were forgotten ($M=0.33 \mu\text{S}$; $d=.35$, 95% CI: $-.3$ to $.9$). *Delayed* free recall results showed that SCRs to the correctly recalled unpleasant and taboo words were larger than to those that were forgotten (unpleasant: remembered $M=0.48 \mu\text{S}$, forgotten $M=0.33 \mu\text{S}$; $d=.28$, 95% confidence intervals: $-.36$ to $.92$; taboo: remembered $M=0.53 \mu\text{S}$, forgotten $M=0.4 \mu\text{S}$; $d=.23$, 95% CI: $-.41$ to $.86$). Differences in response to the recalled versus forgotten words of the other categories were much smaller in magnitude ($d_s<0.15$) from both immediate and delayed free recall. This finding suggests that differential SCRs to arousing word groups predicts subsequent recall.

3.6. Heart rate responses

Fig. 2 shows lowess curves of the mean heart rate change in each 500 ms bin after word presentation by word category. Each of these curves displays a heart rate deceleration immediately following word presentation followed by a relative acceleration. Permutation testing shows that the deceleration in response to the unpleasant words was greater than to the other word types. This is a similar pattern of response to that observed for emotional pictures and sounds (Bradley et al., 2001).

3.7. Heart rate and memory

Heart rate responses to words that were subsequently recalled at immediate and delayed free recall were analyzed

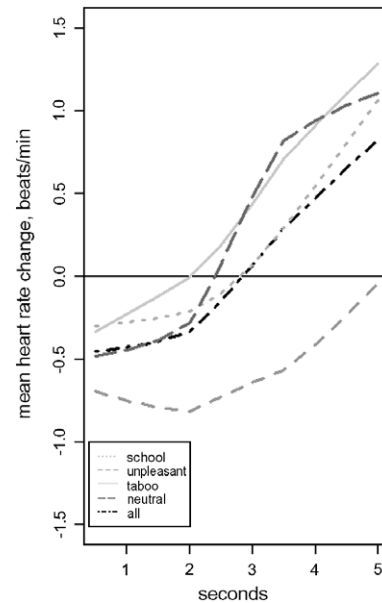


Fig. 2. Lowess curves of mean heart rate change in each 500 ms bin, by word category. The dark dotted line represents the average response across all word types, demonstrating the initial deceleration followed by acceleration responses.

to examine the role of heart rate response to individual stimuli on subsequent memory. Heart rate decelerated more than expected by chance (outside the 95% null bands) for unpleasant and neutral/unrelated words that were subsequently recalled compared to those that were forgotten. This pattern was only statistically significant for immediate recall (see Fig. 3A), though a similar pattern was shown for delayed recall (see Fig. 3B). Taboo words showed a different pattern: less heart rate deceleration was associated with correct recall, though this pattern was not statistically reliable. Deceleration curves for recalled and forgotten school-related words were not significantly different. Similar analyses conducted using recognition memory data did not show the same pattern, perhaps due to the fact that very few words were incorrectly recognized.

4. Discussion

Results from this study replicate previous work showing that semantic relatedness confers as much of an advantage to verbal memory as emotion does. We extend these findings by showing the effects of semantic relatedness and emotional arousal are additive in enhancing memory performance and that event-related autonomic activity is related to subsequent memory performance. Heart rate deceleration and skin conductance responses to subsequently remembered unpleasant words were more pronounced than responses to subsequently forgotten words. This pattern was also found for heart rate responses to neutral/unrelated words: those words producing a more pronounced heart rate deceleration were more likely to be remembered later. In contrast to unpleasant words, taboo words that elicited greater SCRs and heart rate *acceleration* were better remembered (though this pattern was not statistically reliable). These patterns were not found for semantically

Table 3
Skin conductance responses by word category

Category	Mean	SEM
Neutral	0.37	0.13
School	0.38	0.12
Unpleasant	0.38	0.14
Taboo	0.48	0.15

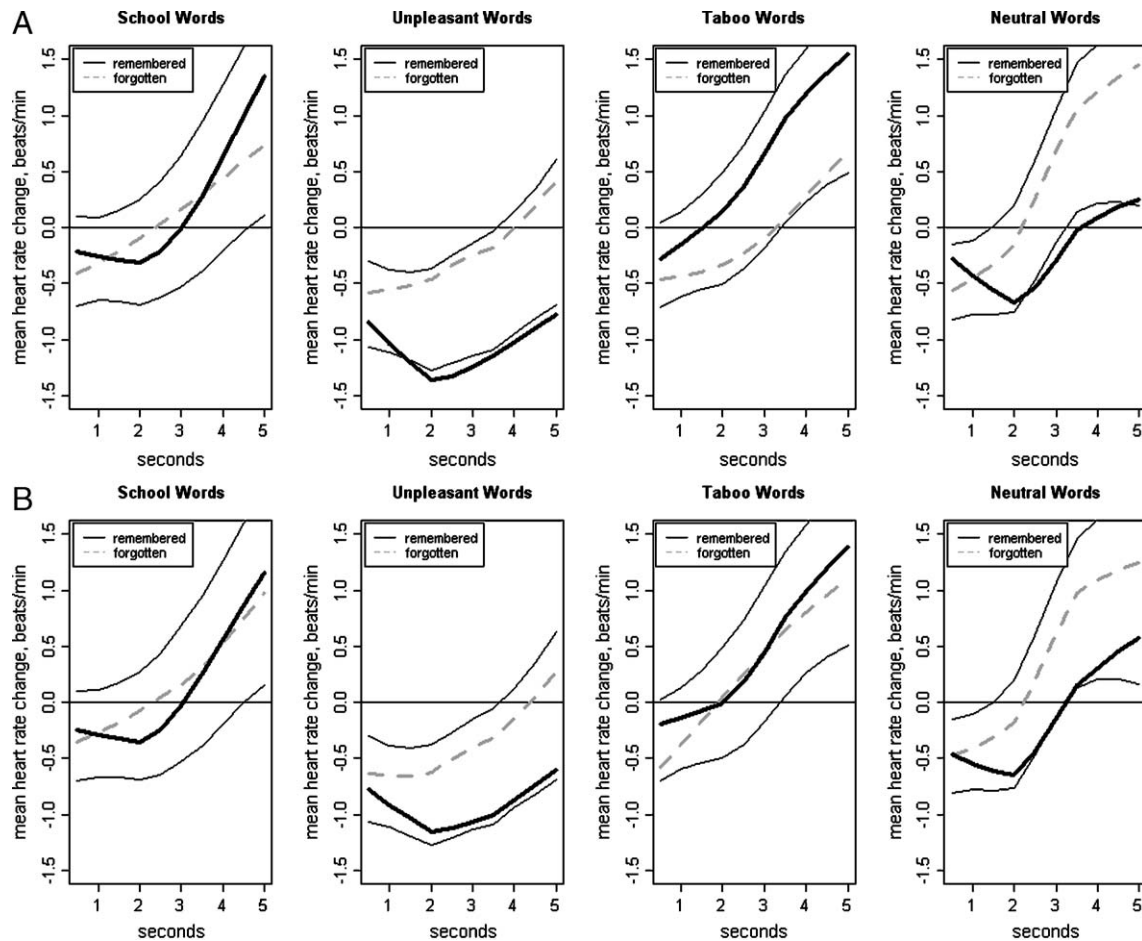


Fig. 3. Lowess curves of mean heart rate change in each bin conditionalized by (A) immediate and (B) delayed free recall performance across word categories, along with 95% null bands (light gray solid lines). Null bands indicate where the lowess curves describing the data fall under the null hypothesis (no relationship between the heart rate changes and type of stimulus or recall). If the true lowess line fall outside its null bands, the line is considered unlikely to have occurred by chance. Dark solid lines represent the heart rate responses to subsequently recalled words. Light dashed lines represent the heart rate responses to subsequently forgotten words.

related neutral (school-related) words. These results demonstrate that autonomic responses to individual words influences subsequent memory and that semantic relatedness is not the only determinant for increased memory of emotional words.

Previous work has documented that emotional words derive their enhanced memorability from some combination of emotional arousal and semantic cohesion (Maratos et al., 2000; Talmi and Moscovitch, 2004). Talmi and Moscovitch (2004) varied the semantic cohesion and emotional arousal of to-be-remembered words and found that semantically related neutral words are remembered as well as emotional words. Both semantically related neutral and emotional words were better remembered than a list of neutral/unrelated words. Our SCR and heart rate results suggest that when semantic relatedness is controlled, differences in arousal within a stimulus set play a role in the subsequent memory of stimuli within that set.

The present findings show the effects of semantic cohesion and arousal to be additive: controlling for semantic cohesion, the emotionally arousing taboo words (which are highly arousing and semantically related) were better remembered than the low arousal school-related words. This effect was found for both free recall and recognition. High semantic

cohesion and/or arousal in the school-related and taboo words improved discriminability (d' ; higher hit rate and lowered false alarm rate) in recognition memory. This finding is consistent with work by (Kensinger and Corkin, 2003), who showed that taboo words are more vividly remembered than low arousal negative-valenced words and with Maratos et al. (2000), who showed a greater false alarm rate for negative compared to neutral/unrelated words. In our study, low to moderate arousal (in the neutral/unrelated and unpleasant word groups) and low semantic cohesion (in the neutral/unrelated word group) led to lowered discriminability indices (lower hit rate and higher false alarm rate). These findings suggest that low arousal and low semantic cohesion reduces discriminability compared to words that are high in either category (or especially to those words high in both categories).

Studies have demonstrated event-related potential (ERP) and functional neuroimaging correlates of successful encoding (Brewer et al., 1998; Fabiani et al., 1986; Paller et al., 1987; Wagner et al., 1998). In these studies, ERPs or cerebral blood flow data are collected while to-be-remembered stimuli are presented. Subsequent recall or recognition is then used to classify the stimuli as either remembered or forgotten.

Electrophysiology results show an increased P300 response elicited to stimuli that are subsequently remembered versus those that are forgotten. Similarly, fMRI data show that increased activity in the prefrontal cortex and parahippocampal gyri predicts subsequent memory performance (Brewer et al., 1998; Wagner et al., 1998). This greater response is presumed to indicate successful encoding operations.

Results from the current experiment demonstrate a similar subsequent memory effect for autonomic activity. Skin conductance responses and heart rate decelerations were greater for unpleasant words that were subsequently remembered compared to those that were forgotten. A similar pattern was found between heart rate deceleration and memory for neutral/unrelated words. These patterns were not found, however, for the taboo or school-related words. In fact, remembered taboo words elicited a non-significant heart rate *acceleration* compared to those that were forgotten. These findings suggest that within a group of low to moderately arousing words, those that produce an autonomic response are the most likely to be remembered. Semantically related words may receive their memory enhancement through cognitive mechanisms such as improved accessibility in retrieval processes (Tulving and Pearlstone, 1966). One mechanism by which emotional words may be better remembered is through enhanced attentional encoding brought on by an orienting response (Sokolov, 1963). Future work could address this possibility by examining the full complement of orienting response measures during the encoding of emotional material.

Presentation of the stimuli used in the current experiment resulted in a similar pattern of autonomic response as that previously documented for emotional pictures and sounds (Bradley et al., 2001; Bradley and Lang, 2000). Emotionally arousing taboo words resulted in significantly increased skin conductance responses compared to the neutral/unrelated words. Heart rate deceleration, by contrast, was greatest and most prolonged in response to unpleasant word presentation. Heart rate responses to the more arousing taboo words did not show such a pronounced deceleration, however. Previous work has shown that the heart rate deceleration response is greatest to unpleasant pictures (Bradley et al., 2001; Palomba et al., 1997). These authors did not show differences in deceleration based on the arousal of the unpleasant picture stimuli. Pleasant pictures tend to produce less of a deceleration than to either unpleasant or neutral pictures. The taboo words used in this experiment constitute a mixed group of positive and negative words that produce variable reactions in individual subjects. The words were rated as less unpleasant, but more arousing than the unpleasant word group. This pattern of mixed valence and high arousal may have led to the pattern of heart rate responses to the taboo words. We cannot say from these data whether this pattern is related solely to arousal or to some combination of other factors.

While this study examined the influences of semantic relatedness and emotional arousal on memory, it should be noted that these factors were not orthogonally manipulated. To fully examine the independent contributions of these factors to memory, the inclusion of a high arousal/semantically unrelated

group of words would be necessary. Other research has shown that arousal may have differential effects on short-term versus long-term memory (LaBar and Phelps, 1998). Our results did not show a difference between immediate and delayed free recall, but these recall sessions were within a short time frame (one hour) and so it is possible that the differential effects of arousal could develop more gradually. Additionally, it is difficult to tease apart the effects of arousal and semantic relatedness in the taboo word category.

Another important caveat to this study is the fact that the use of school-related words as an emotionally neutral category is problematic for the university student participants that were tested. These words may have been more personally relevant to the subjects than the other word categories. Importantly, however, these words were not rated differently from the neutral/unrelated words on either valence or arousal, nor was there a difference in the semantic relatedness of these words compared to the other categories (as assessed by independent raters). We believe, therefore, that these words were well-matched to the other word categories for the purposes of this investigation. While other researchers have used this group of words for similar research (Dillon et al., 2003), we note that future work should perhaps choose a group of words unrelated to the current occupation (or preoccupation) of the participants to be tested.

These results show that both semantic cohesion and emotional arousal (measured through subjective response and psychophysiology) confer a memory advantage to verbal materials. This advantage is additive in the case of taboo words, which were highly arousing, semantically related and remembered best among the word groups. Autonomic responses to words additionally play a role in enhancing memory. While the organization provided by semantic cohesion contributes toward the enhanced memory for emotional words, these results demonstrate an additional effect of autonomic arousal to the memory enhancement.

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References

- Adolphs, R., Cahill, L., Schul, R., Babinsky, R., 1997. Impaired declarative memory for emotional material following bilateral amygdala damage in humans. *Learning and Memory* 4 (3), 291–300.
- Blair, I.V., Urland, G.R., Ma, J.E., 2002. Using Internet search engines to estimate word frequency. *Behavior Research Methods, Instruments, and Computers* 34, 286–290.
- Bradley, M.M., Lang, P.J., 1999. Affective Norms for English Words. NIMH Center for the Study of Emotion and Attention, Gainesville, FL.
- Bradley, M.M., Lang, P.J., 2000. Affective reactions to acoustic stimuli. *Psychophysiology* 37 (2), 204–215.
- Bradley, M.M., Greenwald, M.K., Petry, M.C., Lang, P.J., 1992. Remembering pictures: pleasure and arousal in memory. *Journal of Experimental Psychology. Learning, Memory, and Cognition* 18 (2), 379–390.
- Bradley, M.M., Codispoti, M., Cuthbert, B.N., Lang, P.J., 2001. Emotion and motivation: I. Defensive and appetitive reactions in picture processing. *Emotion* 1, 276–298.

- Brewer, J.B., Zhao, Z., Desmond, J.E., Glover, G.H., Gabrieli, J.D., 1998. Making memories: brain activity that predicts how well visual experience will be remembered. *Science* 281 (5380), 1185–1187.
- Buchanan, T.W., Adolphs, R., 2004. The neuroanatomy of emotional memory in humans. In: Reisberg, D., Hertel, P. (Eds.), *Memory and Emotion*. Oxford University Press, New York.
- Buja, A., Rolke, W., submitted for publication. Calibration for simultaneity: (re)sampling methods for simultaneous inference with applications to function estimation and functional data.
- Cahill, L., 2000. Modulation of long-term memory storage in humans by emotional arousal: adrenergic activation and the amygdala. In: Aggleton, J. (Ed.), *The Amygdala*. Oxford University Press, Oxford.
- Cahill, L., Gorski, L., Belcher, A., Huynh, Q., 2004. The influence of sex versus sex-related traits on long-term memory for gist and detail from an emotional story. *Consciousness and Cognition* 13, 391–400.
- Canli, T., Zhao, Z., Brewer, J., Gabrieli, J.D., Cahill, L., 2000. Event-related activation in the human amygdala associates with later memory for individual emotional experience. *Journal of Neuroscience* 20 (19), RC99.
- Canli, T., Desmond, J.E., Zhao, Z., Gabrieli, J.D., 2002. Sex differences in the neural basis of emotional memories. *Proceedings of the National Academy of Sciences of the United States of America* 99 (16), 10789–10794.
- Cleveland, W.S., 1981. LOWESS: a program for smoothing scatterplots by robust locally weighted regression. *The American Statistician* 35, 54.
- Cohen, J., 1988. *Statistical Power Analysis for the Behavioral Sciences*, 2nd ed. Lawrence Erlbaum, Hillsdale, NJ.
- Diggle, P., 2002. *Analysis of Longitudinal Data*. Oxford University Press, New York.
- Dillon, D.G., Cooper, J.J., Jong, T., Woldorff, M.W., LaBar, K.S., 2003. ERPs dissociate arousal, valence, and semantic cohesion effects during emotional stimulus encoding. *Abstracts - Society for Neuroscience*.
- Edgington, E.S., 1995. *Randomization Tests*. Marcel Dekker, New York.
- Etzel, J.A., Johnsen, E.L., Dickerson, J.A., Adolphs, R., 2004. A program to accurately identify peaks in respiration and EKG signals for use in psychophysiological research. *Psychophysiology* 41, S73.
- Fabiani, M., Karis, D., Donchin, E., 1986. P300 and recall in an incidental memory paradigm. *Psychophysiology* 23, 298–308.
- Francis, W.N., Kucera, H., 1982. *Frequency Analysis of English Usage: Lexicon and Grammar*. Houghton Mifflin, Boston.
- Geer, J.H., McGlone, M., 1990. Sex differences in memory for erotica. *Cognition and Emotion* 4, 71–78.
- Hamann, S., 2001. Cognitive and neural mechanisms of emotional memory. *Trends in Cognitive Sciences* 5 (9), 394–400.
- Jane, R., Blasi, A., Garcia, J., Laguna, P., 1997. Evaluation of an automatic threshold based detector of waveform limits in Holter ECG with the QT database. Paper presented at the *Computers in Cardiology*.
- Jennings, J.R., Hall, S.W., 1980. Recall, recognition, and rate: memory and the heart. *Psychophysiology* 17, 37–46.
- Kahneman, D., Tursky, B., Shapiro, D., Crider, A., 1969. Pupillary, heart rate, and skin resistance changes during a mental task. *Journal of Experimental Psychology* 79, 164–167.
- Kensinger, E.A., Corkin, S., 2003. Memory enhancement for emotional words: are emotional words more vividly remembered than neutral words? *Memory and Cognition* 31, 1169–1180.
- Kensinger, E.A., Corkin, S., 2004. Two routes to emotional memory: distinct neural processes for valence and arousal. *Proceedings of the National Academy of Sciences of the United States of America* 101, 3310–3315.
- Kleinsmith, L.J., Kaplan, S., 1963. Paired-associate learning as a function of arousal and interpolated interval. *Journal of Experimental Psychology* 65, 190–193.
- LaBar, K.S., Phelps, E.A., 1998. Arousal-mediated memory consolidation: role of the medial temporal lobe in humans. *Psychological Science* 9 (6), 490–493.
- Ludbrook, J., Dudley, H., 1998. Why permutation tests are superior to *t* and *F* tests in biomedical research. *The American Statistician* 52, 127–132.
- Maratos, E.J., Allan, K., Rugg, M.D., 2000. Recognition memory for emotionally negative and neutral words: an ERP study. *Neuropsychologia* 38 (11), 1452–1465.
- Moody, G.B., Mark, R.G., Goldberger, A.L., 2001. PhysioNet: a Web-based resource for the study of physiologic signals. *IEEE Engineering in Medicine and Biology Magazine* 20, 70–75.
- Murnen, S.K., Stockton, M., 1997. Gender and self-reported sexual arousal in response to sexual stimuli: a meta-analytic review. *Sex Roles* 37, 135–153.
- Paller, K.A., Kutas, M., Mayes, A.R., 1987. Neural correlates of encoding in an incidental learning paradigm. *Electroencephalography and Clinical Neurophysiology* 67, 360–371.
- Palomba, D., Angrilli, A., Mini, A., 1997. Visual evoked potentials, heart rate responses, and memory to emotional pictorial stimuli. *International Journal of Psychophysiology* 27, 55–67.
- Rubin, D., Schulkind, M., 1997. Distribution of important and word-cued autobiographical memories in 20-, 35-, and 70-year-old adults. *Psychology and Aging* 12, 524–535.
- Snodgrass, J.G., Corwin, J., 1988. Pragmatics of measuring recognition memory: applications to dementia and amnesia. *Journal of Experimental Psychology. General* 117, 34–50.
- Sokolov, E.N., 1963. *Perception and the Conditioned Reflex*. Pergamon, Oxford.
- Talmi, D., Moscovitch, M., 2004. Can semantic relatedness explain the enhancement of memory for emotional words? *Memory and Cognition* 32, 742–751.
- Tulving, E., Pearlstone, Z., 1966. Availability versus accessibility of information in memory for words. *Journal of Verbal Learning and Verbal Behavior* 5, 381–391.
- Wagner, A.D., Schacter, D.L., Rotte, M., Koutstaal, W., Maril, A., Dale, A.M., Rosen, B.R., Buckner, R.L., 1998. Building memories: remembering and forgetting of verbal experiences as predicted by brain activity. *Science* 281, 1188–1191.