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Role of the Left Amygdala and Right Orbital Frontal Cortex in Emotional Interference Resolution Facilitation in Working Memory

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Abstract

Previous research has shown that emotional information aids conflict resolution in working memory (Levens and Phelps, 2008). Using a Recency-probes working memory (WM) paradigm, Levens and Phelps found that positive and negative emotional stimuli reduced the amount of interference created when information that was once relevant conflicted with currently relevant information, suggesting that emotional information facilitates interference resolution in WM. To determine what regions of the prefrontal cortex (PFC) and temporal lobes are critical to the influence of emotional stimuli on interference resolution, we conducted a Recency-probes emotion paradigm with right and left unilateral frontal and temporal lobe lesion patients. The frontal lobe lesion patient group comprised individuals with unilateral ventral and dorsal PFC lesions. The temporal lobe lesion patient group comprised individuals with lesions of the amygdala and surrounding structures. Results indicate that when the left amygdala is damaged, emotional facilitation of interference resolution is absent (equal emotional and neutral interference levels), when the right orbital frontal cortex (OFC) is damaged, in contrast, emotional interference resolution is impaired (emotional interference levels are higher than neutral levels are). Based on these unique patterns we propose specific contributions for these regions in the emotional facilitation of interference resolution in WM.

Keywords

interference resolution; emotion; working memory; orbital frontal cortex; amygdala; prefrontal cortex

Emotion continually influences decisions and behaviors, and research documenting the effect of emotion on working memory (WM) and executive control is increasing. The amygdala, ventromedial prefrontal cortex (VMPFC), anterior cingulate, insula, nucleus accumbens and basal ganglia, for example, are all involved in emotion processing and executive control in some capacity (Hikosaka, Nakamura, & Nakahara, 2006; Luu, Collins,

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Tucker, 2000; Kringelbach, 2005; Pessoa, 2009; Phelps et al., 1998; Wager & Barrett, 2004). We have yet to define, however, the neural regions and processes that integrate affect and executive control in WM. The goal of this study is to determine whether the VMPFC and temporal lobes are critical to the influence of emotional stimuli on interference resolution in WM.

Prior emotion and WM research has illustrated that negative and positive emotional stimuli facilitate interference resolution in WM (Levens & Phelps, 2008). Levens and Phelps used the Recency-probes paradigm with emotional and neutral stimuli to examine how highly arousing positive and negative emotional stimuli affected interference resolution. The Recency-probes paradigm, based on research by Monsell (1978), induces interference between currently relevant information and information that was, but is no longer, relevant. On select trials, source recognition and familiarity are placed in conflict to induce interference that must be resolved. The interference lengthens reaction times, enabling interference to be operationally measured as the reaction time difference between trials with interference and those without. Comparing reaction times between trials with and without interference for neutral and emotional stimuli, Levens and Phelps (2008) found that interference was resolved faster for emotional than for neutral stimuli. They speculated that emotional information contains contextual cues that enhance source recognition and thereby aids interference resolution for emotional material.

To determine what neural regions may underlie the emotional facilitation of interference resolution, the Recency-probes emotion paradigm was conducted in a functional magnetic resonance imaging (fMRI) scanner (Levens & Phelps, 2010). Results reveal a left and right interior frontal gyrus (IFG) region that differentiated between interference and non-interference trials across *all* neutral and emotional stimuli, (2) a region of the left anterior insula and right orbital frontal cortex (OFC) that differentiated between interference and non-interference trials for emotional stimuli, regardless of valence, (3) additional insula, OFC and ventral anterior cingulate cortex (ACC) regions that are sensitive to interference resolution for a select valence and (4) that the left amygdala differentiated emotional and neutral stimuli at encoding and response.

While informative of what regions may be involved in the emotional facilitation of interference resolution in WM, these findings do not reveal the specific contributions of these regions in emotional interference resolution. While the general role of the IFG in interference resolution in WM is established, (Thompson-Shill et al., 2002) the role of the amygdala, OFC and insula in emotional interference resolution is unclear. Do the amygdala and OFC, which have been previously implicated as critical to generating neural signals in response to emotionally arousing stimuli (LeDoux, 1996; Phelps et al., 1998; Rolls, 1996 & 2004) make similar neural contributions, suggesting overlapping roles? Or, do they contribute unique neural signals suggesting distinct roles, and if this is the case, what is the unique role of each region?

To determine the role of the OFC and the amygdala in emotional interference resolution, we conducted a Recency-probes emotion paradigm with right and left unilateral frontal and temporal lobe lesion patients. The frontal lobe lesion patient group comprised individuals with unilateral ventral and dorsal PFC lesions. The temporal lobe lesion patient group comprised individuals with unilateral temporal lobe lesions in the amygdala and surrounding structures. While both the OFC and amygdala have been extensively implicated in processing emotional stimuli and both regions have been found to play a role in emotional interference resolution, there are collective differences in the contribution each region makes in processing emotional information. The OFC, for example, is more consistently linked to the regulation and control of emotion, specifically the temporal monitoring of emotional

information for reward and contingency changes (Hikosaka, 2006; Rolls, 1996, 2004), while the amygdala is implicated in emotion processing, emotional learning, and the expression of learned emotional responses that require the processing of relevant arousing emotional stimuli (Davis, 1997; LeDoux, 1996; Phelps, LaBar, et al., 1998). The amygdala is also implicated in processing of relevance more generally (Sander, Grafman, & Zalla, 2003). We predict that both the OFC and amygdala are critical to emotion interference resolution; however, each region will contribute a unique neural signal, the absence of which will result in a distinct emotion versus neutral interference resolution pattern.

Methods

Overview

In this experiment we ran a modified Recency-probes task on unilateral frontal and temporal lesion patients and age-matched controls to assess whether the right OFC and right and left amygdala are critical to the emotional facilitation of interference resolution. Each trial in the Recency-probes task consisted of two separate displays: a 2 second target set display of three words followed by a 2 second delay, and a 2 second single probe word display followed by a variable inter-trial interval (ITI) delay. Participants were asked to respond as quickly and accurately as possible as to whether or not the single probe word had appeared in the previous target set of three words. Participants responded by pressing one of two keys on a button box: they pressed the key under their index finger to respond “Yes” if they thought the probe word was in the previous target set, and the key under their middle finger to respond “No” if they thought the word was not in the previous target set. Participants’ responses and the latency of their key presses were recorded.

Words within the trial blocks differed in valence (neutral, positive, or negative) to measure the influence of emotion on interference resolution. Reaction times and interference levels were compared between neutral and negative stimuli, and between neutral and positive stimuli across the lesion groups.

Subjects

Twenty one patients with unilateral brain damage identified on the basis of magnetic resonance imaging (MRI) scans, were recruited from New York University’s Comprehensive Epilepsy Center. Exclusion criteria included early onset epilepsy as well as any other medical or neurological diseases aside from epilepsy. Subjects were tested a minimum of 1 year after surgery. A control group of 25 age-matched healthy participants with no history of neurological disease was recruited by advertisements in the local community. None of the subjects had a history of psychiatric problems or substance abuse, and all had an IQ of 90 or above. All participants were paid for their participation and provided written, informed consent; the study protocol was approved by the institutional review board of New York University. Background information for all subjects is provided in Table 1.

Lesion analysis

Lesions were traced from available CT or MRI scans on to a standardized brain using MRIcro software (Rorden and Brett, 2000). The subjects were divided into 2 groups based on whether the lesion was located in the frontal or temporal lobes. The temporal lobe lesions included the amygdala and surrounding cortices, and the frontal lobe lesions comprised both ventral and dorsal lesions. Figure 2 shows the location and degree of overlap for both the temporal and frontal lobe lesion participants. Lesions were due to surgery to remove seizure foci. The lesion patient participants were further divided based on lesion laterality: right

temporal lobe lesion, left temporal lobe lesion, right frontal lobe lesion and left frontal lobe lesion (see Table 1).

Stimuli

A total of 590 emotional and neutral words (260 emotional and 330 neutral) from the Affective Norms for English Words (ANEW) battery developed by Bradley and Lang (1999) were selected as stimuli. Each set of words was selected based on ANEW valence and arousal ratings. The neutral words (e.g., 'chair') formed one large category of words; the emotional words were separated into two categories: one consisting of negative valence, high arousal words (e.g., 'mutilation,' 'terror,' 'murder'), and the other consisting of positive valence, high arousal words (e.g., 'desire,' 'treasure,' 'erotic'). Words within the neutral and emotional categories were balanced for frequency of use and word type (nouns vs. adjectives). The mean, range, and standard deviations of ratings, frequency and word type of all stimuli are presented in Table 2.

Task Design

The experiment was divided into two 30-minute sessions: the Positive session consisted of positive and neutral words as stimuli, and the Negative session consisted of negative and neutral words as stimuli. The presentation order of the two sessions was counterbalanced across subjects. The two sessions were performed in one day with a 15 minute break in between to avoid fatigue. The experimental procedure was similar for each session. Instructions about the experiment were given to participants both orally and in writing. The experiment consisted of 360 trials separated into 12 blocks of 30 trials, as well as an additional 16 practice trials that were not scored. For each session, participants completed 8 practice trials followed by 180 experimental trials separated into 6 blocks of 30 trials. Each trial consisted of a target set of three words displayed on the computer screen for 2000 ms., followed by a delay of 2000 ms. during which a fixation cross was presented, followed by the presentation of a single probe word for 2000 ms. A variable inter-trial-interval of 2000 or 4000 ms. occurred after each probe and before the next target set presentation. Participants were instructed to indicate as quickly and as accurately as possible whether or not the probe word matched a word in the current target set by pressing buttons corresponding to 'Yes' or 'No' on the computer keyboard.

Emotional words within the Positive and Negative sessions were placed strategically to permit an examination of the effects of emotional content on response selection in the context of interference. Trial target sets had a minimum of one emotional word and a maximum of three emotional words; the majority of trials had two emotional words (57 trials had one emotional word, 267 trials had two emotional words, and 36 trials had three emotional words). To delineate the effect of emotional content on interference resolution when the emotional information is the focus of the trial versus when it is not the focus of the trial, two valence conditions were defined in each valence session: a Neutral valence condition, which included trials with all neutral words, and an Emotion valence condition, which consisted of trials in which the probe words were emotional (see Figure 1 for trial examples). The presentation order of neutral and emotion blocks within each session was counterbalanced, as were individual trials within a block, so that 'No' and 'Yes' responses were equally likely to precede/follow each other.

Within each session the Emotion condition is referred to by its specific valence (i.e. the Negative valence condition and the Positive valence condition). Furthermore, all data focused on No-response trials; Yes-response trials were not included in the analysis since they did not include any interference manipulations (D'Esposito et al., 1999; Levens & Phelps, 2010). The No-response experimental trials were separated into two trial types: (1)

Recent No-response trials, in which the probe does not match any items in the target set of the present trial but does match an item from the target set of the past two trials, and (2) *Non-recent No-response* trials, in which the probe does not match items from the current or the past two target sets.

Interference was present in the *Recent No-response* trials because the probe word was not a member of the current target set, but was a member of the preceding two target sets, thereby creating interference between a ‘familiarity’ based response of ‘yes’ and a ‘source’ response of ‘no.’ Familiarity and source recognition, while normally in concert, were placed in conflict in this task: whereas source recognition supported a correct “No” response, familiarity supported an incorrect “Yes” response. Both the source and familiarity representations inform participants how to respond to the current trial. To respond correctly on interference trials, however, participants must select the source representation rather than the familiarity representation to inform their response. Because the interference must be resolved before the individual can respond, RTs in Recent No-response trials, or interference trials, are longer than in Nonrecent No-response trials, or non-interference trials (D’Esposito et al., 1999). The difference between Recent No-response and Nonrecent No-response trials, therefore, represents the amount of interference that must be resolved in Recent No-response trials to select the correct source representation required to make a response.

Data Analysis

Incorrect trials and individual outlier trials greater than 3 standard deviations from the subject’s trial type mean were excluded from all analyses (7 control subjects and 9 lesion subjects had 1–3 individual trial reaction times (of their 360 total trials) removed from analysis). Two separate analyses were conducted between lesion patients and controls. First, a patient “whole group” reaction time analysis was conducted between patients and controls to replicate prior neutral (Jonides et al., 1998) and emotional (Levens & Phelps, 2008 & 2010) interference resolution findings, and to examine any baseline reaction time differences between the two groups. For this analysis, all patients’ behavioral data was combined to form one large patient group, which was then compared with controls via a $2 \times 2 \times 2$ ANOVA comparing Valence Condition (Neutral and Emotion), Recency (interference and noninterference) and Group (Patients and Controls). This ANOVA was conducted twice: once for the Negative session and once for the Positive session.

Second, to examine the effect of a specific brain region on interference resolution for neutral and emotional stimuli, a lesion location analysis was conducted between patients and controls that involved two steps. Patients were divided into four groups based on lesion location: left lobe, right temporal lobe, left frontal lobe, and right frontal lobe. In step one, an *interference score* was calculated for each valence condition for each person. The interference score is the reaction time difference between interference trials and non-interference trials. It represents the amount of interference created in a given valence condition. Interference scores were generated for the Neutral and Emotional valence conditions of each session and compared two ways, one, within each lesion group using a Wilcoxon Signed-Rank Test, the nonparametric equivalent of a paired t-test recommended for small sample sizes, and two, between each lesion group and controls to examine level of interference as a function on lesion location.

Finally, in step two, to measure emotional facilitation of interference resolution as a function of lesion location, an *emotional facilitation* score was calculated for each participant’s valence sessions. The emotional facilitation score is a measure of the magnitude of emotional facilitation—the decrease in interference from Neutral to Emotion valence condition trials. To calculate the emotional facilitation score, Emotion condition interference scores were subtracted from Neutral condition interference scores in each valence session, a

positive facilitation score, therefore, indicates less emotional than neutral interference and emotional facilitation of interference resolution.

Based on the design of the Recency-probes emotion paradigm, there are two types of abnormal emotional interference resolution behavior patterns that can occur: emotion interference resolution can be *impaired* or it can be *absent*. *Impaired emotion interference resolution* means that interference levels in the emotion valence condition are *higher* (vs. lower) than interference levels in the neutral valence condition, a pattern opposite that shown by controls. *Absent emotional facilitation*, in contrast, means that interference levels in the emotion valence condition are the *same* as (vs. lower than) interference levels in the neutral valence condition. If a lesion group did not show the expected interference pattern of significantly less emotion than neutral interference, a group and individual subject analysis was conducted that compared facilitation scores within the group to controls. For the individual subject analysis, if patients in any of the lesion groups showed a facilitation score that was over 2 standard deviations away from the control group mean, they were grouped by lesion location and compared to controls via an independent sample Mann-Whitney test, a nonparametric test suitable for comparing small sample sizes. All patient and control reaction times, interference levels and facilitation scores are presented in Table 3.

Results

The results are presented in five sections. In the first section, controls are compared with patients in an overall reaction time and error rate group analysis. In the second through fifth sections, the interference scores are analyzed by lesion location: right temporal lobe (second), left temporal lobe (third), right frontal lobe (fourth), and left frontal lobe (fifth). Within each lesion group, Negative valence session findings are presented first, followed by Positive valence session findings and a summary paragraph. Within each valence session of each lesion group, the results of any individual subject analyses are presented.

Overall Group Analysis

Negative valence session—Reaction times for patients and controls are presented in Table 3. The Emotion condition by Recency by Group ANOVA revealed a main effect of Recency, $F(1,44)=106.56$, $p<0.001$ $\eta=.71$, and a Recency by Emotion interaction, $F(1,44)=7.086$, $p<0.01$ $\eta=.139$, qualified by a Recency by Emotion by Group interaction, $F(1,44)=4.241$, $p<0.05$ $\eta=.088$. No other main effects or interactions were significant. Follow up t-test conducted to examine the Recency main effect revealed that the data replicates the basic proactive interference effect identified by Jonides et al. (1998) and D'Esposito et al. (1999): interference trial reaction times were significantly longer than the non-interference trial reaction times, $t(45)=10.05$, $p<0.001$. To examine the Recency by Emotion interaction, interference scores in the Neutral and Emotion valence conditions were compared. Results reveal that interference levels in the Neutral condition were significantly higher than interference levels in the Emotion condition, $t(45)=2.75$, $p<0.01$, replicating the emotional facilitation of interference resolution effect found previously (Levens and Phelps, 2008 & 2010). To examine the three-way Recency by Emotion by Group interaction, an emotional facilitation score, a measure of the magnitude of emotional facilitation—or the decrease in interference from Neutral to Emotion condition trials, was calculated for each participant. The emotional facilitation score is the Neutral condition interference score minus Emotion condition interference score from each valence session; a positive score indicates emotional facilitation of interference resolution. For instance, for control subjects the mean Negative Valence condition facilitation score is 74 ms. (SD=79) indicating that controls are on average 74 ms. faster at resolving emotional than neutral interference trials, the mean Negative valence facilitation score of patients however is 9 ms. (SD=130). An independent

sample t-test comparing the facilitation scores of the two groups confirms that the significant three-way interaction is due to patients having significantly lower Negative Valence facilitation scores than controls, $t(44) = 2.059$, $p < 0.05$.

Group error rates for patients and controls are presented in Table 3. The Emotion condition by Recency by Group ANOVA conducted on Negative valence session error rates revealed a main effect of Recency, $F(1,44) = 7.85$, $p < 0.01$ $\eta^2 = .151$, and a main effect of Emotion, $F(1,44) = 46.22$, $p < 0.001$ $\eta^2 = .51$, qualified by a Recency by Emotion interaction, $F(1,44) = 49.22$, $p < 0.001$ $\eta^2 = .528$. No other main effects or interactions were significant. Follow-up paired t-tests indicate the Recency by Emotion interaction is due to significantly higher Nonrecent No-response error rates in the Emotion than Neutral condition, $t(45) = 11.43$, $p < 0.001$.

Positive valence session—The Valence condition by Recency by Group ANOVA revealed a main effect of Recency, $F(1,44) = 65.883$, $p < 0.001$ $\eta^2 = .6$, qualified by a Recency by Valence condition interaction, $F(1,44) = 32.35$, $p < 0.001$ $\eta^2 = .424$. No Group main effects or interactions were significant. Similar to the Negative session, the Recency main effect was due to significantly longer interference than non-interference trial reaction times, $t(45) = 8.127$, $p < 0.001$. Follow-up paired t-tests also revealed that the Recency by Valence condition interaction was due to higher interference levels in the Neutral than Emotion condition, $t(45) = 5.803$, $p < 0.001$.

The Emotion condition by Recency by Group ANOVA conducted on Negative valence session error rates revealed a main effect of Recency, $F(1,44) = 14.11$, $p < 0.01$ $\eta^2 = .243$, qualified by a Recency by Emotion by Group interaction, $F(1,44) = 5.935$, $p < 0.05$ $\eta^2 = .12$. No other main effects or interactions were significant. Follow-up paired t-tests indicate the Recency by Emotion by Group interaction is due to significantly *lower* Patient than Control error rates on Nonrecent No-response trials in both the Neutral and Emotion conditions, $t(44) = 4.25$, $p < 0.001$, and $t(44) = 2.935$, $p < 0.01$, respectively, as well as, lower Patient than Control error rates on Recent No-response trials in the Emotion condition, $t(44) = 3.35$, $p < 0.01$.

Summary—The results from the group analysis replicate prior findings that emotion facilitates interference resolution in working memory (Levens & Phelps, 2008). These results also indicate that patients show less emotion interference resolution facilitation in the Negative Valence condition than controls, but overall similar reaction times and levels of interference in the Positive Valence condition. Furthermore, error rate analysis reveals similar performance across groups in the Negative Valence Condition and better performance on the part of Patients in the Positive Valence condition. To examine the significant group interaction reported in the Negative Valence session and to determine if specific lesion groups may show a neutral and emotional interference level pattern different than that shown by controls that this whole group lesion analysis does not capture, a lesion location analyses and individual subject analyses was subsequently conducted.

Right Temporal Lobe Lesion Group

Negative valence session—Neutral and Emotion interference levels were compared to controls using an independent sample Mann-Whitney test and within group using a Wilcoxon Signed-Rank Test. Results reveal that, neutral and emotional interference levels are statistically similar to those of controls, $z = .751$, $p > .1$ and $z = .640$, $p > .1$ respectively. Results also reveal that, similar to controls, emotional interference levels are significantly lower than neutral interference levels, $z = 2.023$, $p < .05$.

Positive valence session—Similar to the negative valence session, positive valence session neutral and emotional interference levels are statistically similar to those of controls, $z=.696$, $p>.1$ and $z=.195$, $p>.1$ respectively. In addition, similar to controls and to the negative valence session, emotional interference levels are significantly lower than neutral interference levels, $z=2.023$, $p<.05$.

Summary—Our results show no significant effect of right temporal lobe damage on the facilitation of interference resolution for emotional stimuli; similar to controls, right temporal lobe resection patients' emotional interference levels are significantly lower than their neutral interference levels.

Left Temporal Lobe Lesion Group

Negative valence session—Comparisons between patients' and controls' Neutral and Emotion interference scores indicates that interference levels are statistically similar across groups, $z=1.012$, $p>.1$, $z=-.885$, $p>.1$ respectively. However, a within group Wilcoxon Signed-Rank test comparing Neutral and Emotion interference levels reveals that unlike controls, Negative valence session emotional interference levels are *not* significantly lower than neutral interference levels, $z=.703$, $p>.1$, suggesting that no negative emotional facilitation is occurring following left temporal lobe resection. To further examine emotional interference levels within this lesion group, an emotional facilitation score, a measure of the magnitude of emotional facilitation—or the decrease in interference from Neutral to Emotion condition trials, was calculated for each participant. The emotional facilitation score is the Neutral condition interference score minus Emotion condition interference score from each valence session; a positive score indicates emotional facilitation of interference resolution, a score close to 0 suggests absent emotional facilitation, and a negative facilitation score suggests impaired emotional interference resolution. When the facilitation scores of left temporal resection patients were compared to controls, no individual subject facilitation scores were outliers (greater than 2 standard deviations) from the mean control facilitation score, however, as a group, as measured by a Mann-Whitney independent sample test, the facilitation scores of left temporal resection patients are significantly less than those of controls, $z=2.783$, $p<.01$.

Positive valence session—Comparisons between patients' and controls' Neutral and Emotion interference scores indicates that emotional interference levels are statistically similar between controls and left temporal lobe resection patients, $z=1.075$, $p>.1$, however, neutral interference scores are not, with lesion participants reporting significantly less neutral interference than controls. $z=-2.214$, $p<.05$. Similar to the negative valence session, a within group Wilcoxon Signed-Rank test comparing Neutral and Emotion interference levels reveals that unlike controls, Positive valence session emotional interference levels are *not* significantly lower than neutral interference levels, $z=1.823$, $p>.05$, suggesting that no positive emotional facilitation is occurring following left temporal lobe resection. An examination of the facilitation scores of left temporal resection patients confirms that as a group, the facilitation scores of left temporal resection patients are significantly less than those of controls, $z=2.783$, $p<.001$.

Summary—The present data shows that following left amygdala resection there is no significant facilitation of emotional interference resolution; instead interference levels in the emotion condition are similar to interference levels in the neutral condition, reflecting an absence of emotional facilitation. The lesions of left temporal lobe patients are displayed in Figure 4.

Right Frontal Lobe Lesion Group

Negative valence session—Neutral and Emotion interference levels were compared to controls using an independent sample Mann-Whitney test and within group using a Wilcoxon Signed-Rank Test. Results reveal that, neutral and emotional interference levels are statistically similar to those of controls, $z=.417$, $p>.1$ and $z=1.475$, $p>.1$ respectively. However, results also reveal that, unlike controls, emotional interference levels are not significantly lower than neutral interference levels, $z=-.405$, $p>.1$, indicating that negative emotional stimuli do not aid interference resolution in patients with a right frontal resection. To further examine emotional interference levels within this lesion group, the facilitation scores of right frontal resection patients were compared to controls. As a group right frontal lesion patients' facilitations are not significantly different from controls, however of the 5 right frontal patients, two subjects have individual subject facilitation scores that are outliers (greater than 2 standard deviations) from the controls' mean facilitation score: patients J and K. Patient J, with a right frontal lobe resection that includes all of the OFC and Patient K, whose whole right prefrontal cortex was removed, had *higher* emotional than neutral interference levels resulting in a negative facilitation score (-149 and -183 respectively compared to the control mean of 74 ($SD=79$)). All other patient facilitation scores fall within 1 standard deviation of the control mean. An independent sample Mann-Whitney test confirms that the facilitation scores of Patients J and K differed significantly from those of controls, $z=2.315$, $p<0.05$. These *negative* facilitation scores suggest that lesions that include the right OFC result in *impaired* interference resolution for negative emotional stimuli, while dorsal right frontal lobe lesions have no significant effect on interference resolution.

Positive valence session—Similar to the Negative valence session, Neutral and Emotion interference levels were compared to controls using an independent sample Mann-Whitney test and within group using a Wilcoxon Signed-Rank Test. Results reveal that, neutral and emotional interference levels are statistically similar to those of controls, $z=.083$, $p>.1$ and $z=1.419$, $p>.1$ respectively. However, unlike controls, emotional interference levels are not significantly lower than neutral interference levels, $z=.944$, $p>.1$, indicating that positive emotional stimuli do not aid interference resolution in patients with a right frontal resection. To further examine emotional interference levels within this lesion group, the facilitation scores of right frontal resection patients were compared to controls. As a group right frontal lesion patients' facilitation scores are not significantly different from controls, however of the 5 right frontal patients, similar to the negative valence session, patient J has a facilitation score significantly different from the control mean (greater than 2 standard deviations) and patient K has a facilitation score greater than 1.5 standard deviations from the control mean. All other patient facilitation scores fall within 1 standard deviation of the control mean. Similar to the negative valence session, an independent sample Mann-Whitney test confirms that Patient J's and K's facilitation scores differ significantly from the control mean, $z=2.315$, $p<0.05$. Patient J's resection includes all of the OFC and Patient K's resection includes the whole right prefrontal cortex; the high positive facilitation scores of patients' J and K therefore indicate that lesions that include the right OFC result in impaired interference resolution for positive emotional stimuli, while dorsal right frontal lobe lesions appear to have no significant effect on interference resolution.

Summary—Patients J and K show a finding opposite to that of controls—namely, greater interference levels in the Emotion than Neutral conditions. Patient J with a right OFC lesion has consistent negative facilitation scores that are outliers in both the positive and negative valence sessions, and patient K with a right PFC lesion also has an outlier negative facilitation score in the Negative Valence session and a negative facilitation score in the Positive Valence session that is 1.5 standard deviations from the control mean. These

findings suggest that damage to the right OFC impairs emotional interference resolution facilitation. Our results show that other lesions in the right frontal cortex, including lesions to the dorsolateral PFC, have no significant effect on interference resolution for emotional stimuli. The common right OFC region of Patients J and K is shown in Figure 3.

Left Frontal Lobe Lesion Group

Negative valence session—Neutral and Emotion interference levels were compared to controls using an independent sample Mann-Whitney test and within group using a Wilcoxon Signed-Rank Test. Results reveal that, neutral and emotional interference levels are statistically similar to those of controls, $z=.068$, $p>.1$ and $z=1.162$, $p>.1$ respectively. However, unlike controls, emotional interference levels are not significantly lower than neutral interference levels, $z=.169$, $p>.1$, indicating that Negative emotional stimuli do not aid interference resolution in patients with a left frontal resection. To further examine emotional interference levels within this lesion group, the facilitation scores of left frontal resection patients were compared to controls. As a group left frontal lesion patients' facilitation scores are not significantly different from controls, however of the 7 left frontal patients, patients O & P have facilitation scores that are outliers from the control mean (greater than 2 standard deviations) and patient Q has a facilitation score greater than 1 standard deviation from the control mean. All other patient facilitation scores fall within 1 standard deviation of the control mean. Patients O and P whose facilitation scores were greater than 2 standard deviations from the control mean were grouped and compared to controls in an independent sample Mann-Whitney test; results reveal that Patients O's and P's facilitation scores differ significantly from controls, $z=2.315$, $p<0.05$. Patients O, P and Q all have lesions that include the left MFG.

Patient O, whose lesion in addition to the MFG also includes the left IFG, not only has the highest negative facilitation score (−406) but also unusually high reaction times. To further examine whether the interference levels of Patient O are abnormally high regardless of Emotion conditions, a standard deviation analysis was conducted to measure Patient O's deviation from the control mean. Results indicate that the Neutral condition interference level (215) was 1.7 standard deviations from the control mean and the Emotion condition interference level (621) was 8.1 standard deviations from the mean, suggesting that Patient O had higher interference levels than controls for all stimuli.

Positive Valence session—Neutral and Emotion interference levels were compared to controls using an independent sample Mann-Whitney test and within group using a Wilcoxon Signed-Rank Test. Results reveal that, neutral and emotional interference levels are statistically similar to those of controls, $z=.752$, $p>.1$ and $z=.160$, $p>.1$ respectively. Unlike the Negative valence session, results reveal that, similar to controls, emotional interference levels are significantly lower than neutral interference levels, $z=2.366$, $p<.05$. However, similar to the Negative valence session, Patient O again had unusually high interference levels in each condition. While Patient O showed the expected decrease in emotional than neutral interference levels, the interference levels of both the neutral (379) and emotional (233) conditions were greater than two standard deviations (3.5 and 3.2 standard deviations respectively) from the control mean.

Summary—Lesion location comparisons between Patients O, P and Q and the remaining left frontal lesion patients indicate that a lesion to the left MFG region impairs interference resolution for negative stimuli but leaves intact positive emotion facilitation. Patient O, whose more extensive dorsal frontal lobe lesion extends from the MFG dorsally and posteriorly to also include the IFG and precentral gyrus, showed significantly higher levels of interference for all stimuli, possibly indicating generalized interference resolution

impairment. Since Patient O's lesion includes sections of the premotor cortex, the high levels of interference may be due to an impaired ability to respond to the trials as opposed to impaired interference resolution. Patient O's lesion also includes however, portions of the IFG, shown previously by Thompson-Schill et al. (2002) to be critical to interference resolution on this task. Another possibility is that damage to the IFG and not the premotor cortex is responsible for higher levels of interference. Our results show that all other lesions in the left frontal cortex, including lesions to the left OFC and dorsolateral PFC, have no significant effect on interference resolution for emotional stimuli.

Discussion

We sought to determine what regions of the frontal and temporal lobes may be critical to the emotional facilitation of interference resolution. Previous imaging data indicates that the OFC and amygdala are involved in emotional interference resolution, but whether these regions are critical, and if so, what their respective role is in the emotional interference resolution process is unknown. Conducting the Recency-probes emotion paradigm on unilateral frontal and temporal lesion patients resulted in three principle findings. First, damage to the left amygdala and hippocampus resulted in the absence of emotional facilitation of interference resolution: Left temporal lobe lesion patients *all* showed similar levels of interference for negative and neutral stimuli, or positive and neutral stimuli, or both. Second, right OFC lesions impaired emotional interference resolution. Patients J and K, both with right frontal lobe resections including OFC, showed greater interference levels in the Emotion condition than in the Neutral condition for negative and positive stimuli. Third, the left MFG lesions selectively impaired interference resolution for negative stimuli. In addition, Patient O, who had a left MFG lesion that extended dorsally and posteriorly into the precentral gyrus and in the IFG, showed higher levels of interference for neutral, negative and positive stimuli, possibly reflecting a generalized deficit in interference resolution (see also Thompson-Schills et al., 2002).

Based on the behavior patterns demonstrated by left temporal lesion patients and right OFC lesion patients, we conclude that present data demonstrates that the left amygdala and right OFC are both critical to the emotion facilitation effect isolated by Levens and Phelps (2008). Furthermore, the distinct data patterns for each lesion group suggest what possible roles the amygdala and OFC may have in the facilitation of interference resolution for emotional stimuli as well as a more general role for the left MFG in attention and emotion processing. Before discussing the functional role of each region, we review the factors underlying emotional facilitation of interference resolution in WM (for additional discussions see Levens & Phelps, 2008).

Requirements for emotional facilitation of interference resolution

The Recency-probes paradigm manipulates two well-studied memory processes: familiarity and source recognition. The source recognition signal of "No" in Recent No-response trials is put into conflict with the familiarity signal of "Yes". A correct response to a Recent No-response trial thus requires interference resolution processes. Consequently, a decrease in the level of interference requires an increase in source signal strength, or a decrease in familiarity signal strength. While there is no evidence that emotional information would reduce the strength of the incorrect familiarity response, there is evidence of enhanced encoding of source memory for emotional stimuli (Doerksen & Shimamura, 2001; Kensinger & Corkin, 2003; Tabert, Borod, Tang, Lange, Wei, Johnson, Nusbaum, & Buchsbaum 2001) that would subsequently increase the strength of the correct source response to decrease interference thereby facilitating interference resolution for emotional information in WM.

What remains unknown is how emotion affects the attention and selection processes that underlie interference resolution to facilitate emotional interference resolution. A selection model such as Desimone and Duncan's (1995) Biased-Competition model, applied to the Recency-probes paradigm suggests a mechanism by which the emotional content can facilitate interference resolution. According to the Biased-Competition model, selection is mediated by an attention template that consists of properties relevant to the goal of some task (Jonides & Nee, 2006). In the case of this Recency-probes emotion task, the template might include the valence-arousal level for the current block of trials, the probe and target set items and their contextual associations, and any temporal context present in the trial. Since the stimuli are repeated multiple times, the trial template must also be adjusted to include the aforementioned contextual associations for the previous trials. The Biased-Competition model postulates that each item in the current and preceding trial template is linked with a contextual tag and the greater the similarity between the probe's contextual tag and that of the target set, the greater the bias to classify the probe as a member of the target set.

Emotional stimuli are salient, arousing, and involve additional neural processing regions, such as the OFC and amygdala, that allocate more resources to the processing of these stimuli. The additional processing resources results in a more elaborate encoding of context surrounding an emotional stimulus that has two consequences in this paradigm: 1) an increase in the familiarity of an emotional stimulus, and 2) additional emotional context, particularly temporal context, contributing to stronger source representation.

The design of the Recency-probes paradigm provides a measure of how emotional content becomes integrated into the WM system. Emotionally salient information, for example, captures attention, which increases processing resources and results in a higher activation level that may persist into future trials to keep an emotional stimulus active in WM to impact ongoing task processing thereby increasing familiarity (Compton, Banich, Mohanty, Milham, Harrington, Miller, Scaif, Webb, & Heller, 2003; Levens & Phelps, 2008), which, in turn, increases interference (Monsell, 1978). Conversely, the greater attention and processing resources given to emotional stimuli, also leads to more expansive encoding, which will result in the formation of additional emotional context (as compared to neutral information) that will enhance source and reduce interference resolution reaction times for emotional versus neutral stimuli. The later explanation accounts for the present findings of emotional facilitation of interference resolution (Levens & Phelps, 2008). Interestingly, while increases in emotional arousal and salience can be present without enhanced emotional source, enhanced emotional source information is derived from the additional context that salience and arousal information provides (Doerksen & Shimamura, 2001; Kensinger & Corkin, 2003). The emotional facilitation of interference resolution therefore requires two unique neural signals: 1) a saliency/arousal signal that distinguishes emotional from neutral stimuli and 2) an enhanced source signal derived from the initial saliency signal that provides additional contextual information such as temporal context. But what emotion processing region provides which signal? Our lesion findings suggest what neural signals the amygdala, OFC and MFG may provide.

The function of the left Amygdala

Based on the finding of similar emotional and neutral interference levels for individuals with left amygdala resections, and based on the structure of the Recency-probes paradigm, we propose that the left amygdala influences emotional interference by providing salience and arousal signals that differentiate emotional from neutral information. These salience and arousal signals are then sent to other emotion processing regions of the brain to facilitate processing of emotional stimuli. Removing the amygdala therefore removes the salience and arousal signals that affect downstream processes such as encoding and recall in the OFC and

hippocampus. Without salience/arousal signals from the amygdala for example the OFC would be missing critical neutral signals that it uses to evaluate relevance, and temporal and emotional contingency change monitoring (Murray & Izquierdo, 2007; Stalnaker et al., 2007). Similarly the insula, which has been shown to be involved in interference resolution (Wager & Feldman Barret, 2004), would be missing critical emotional salience information, contributing to the similar neutral and emotional condition interference levels observed in left amygdala resection patients.

The present data also suggests that the left amygdala, in particular, is critical for emotional interference resolution foundation. This finding however is expected since the left amygdala has been found to processes *verbal* arousing stimuli and the right amygdala non-verbal stimuli (Engelien et al., 2006; Isenberg et al., 1999). The present task uses verbal stimuli and therefore cannot adequately test the role of the right amygdala in emotional interference for non-verbal stimuli. Prior research has demonstrated emotional facilitation of interferences resolution for pictorial stimuli (Levens & Phelps, 2008), and although pictorial stimuli is often dually (spatially and verbally) encoded, conducting the pictorial emotional Recency-probes task on right amygdala damage patients may reveal that the right amygdala is critical for emotional interference resolution facilitation as well.

The function of the right OFC

Based on our finding that a right OFC lesion results in an increase in interference for emotional information, but not neutral information, we can speculate about the specific role of the right OFC in the emotional facilitation of interference resolution as well. The OFC is central to processing emotional information that requires the temporal monitoring of context (Rolls, 1996 & 2004). In this capacity, it is particularly critical to changes in reward contingency and reversal learning (Hikosaka, 2006; Murray & Izquierdo, 2007; Stalnaker et al., 2007). Since emotional content aids source recognition (Levens and Phelps, 2008) and in the absence of an intact right OFC there is greater interference for emotional stimuli than neutral stimuli (behavioral findings of Patients J and K), then right OFC resection may eliminate the enhanced source signal required to reduce interference. Therefore, we propose that for emotional stimuli, the OFC provides a neutral signal that aids source recognition by providing additional temporal context. Further, when the enhanced source signal is not available to aid interference resolution, such as when the OFC is damaged, the salience signal from the amygdala that differentiates emotional from neutral stimuli, increases familiarity, and supports a 'yes' response, is not deterred, thereby generating *more* interference in the Emotion, but not Neutral, conditions.

Evidence exists, however, that there may be some redundancy between the amygdala and OFC in the processing of emotional stimuli (Pavuluri et al., 2005). The amygdala and OFC have strong reciprocal connections (Croxson et al., 2005) and the interconnectedness of the amygdala and OFC makes it challenging to determine where the initial salience/arousal emotion processing signal originates--the amygdala or the OFC. The results of depth electrode studies are mixed. Krolack-Salmon et al., (2004) for example, have provided evidence that emotional stimulus processing begins in the amygdala at 200 ms. and spreads to the OFC. Kawasaki et al., (2001) in contrast found that emotional stimulus processing begins even earlier in the OFC, at 120–160 ms. Amygdala and OFC lesion research with primates, however, speculates that the amygdala is necessary for the *initial* registration of changes or variations of arousal level, reward, and emotional context (Murray & Izquierdo, 2007). Once the reward value, arousal level, or emotional context has been updated, the information travels upstream to the OFC, which then coordinates future emotional stimulus responses and expectations via its connections with subcortical and neocortical regions such as the insula and other regions in the frontal cortex. Although, the origin of the initial emotional signal that distinguishes emotional from neutral stimuli is up to debate, the

behavioral patterns of amygdala and OFC resection individuals suggests that in this task, the amygdala provides a neural signal that distinguishes emotional from neutral stimuli, while the OFC provides an enhanced source signal that aids interference resolution for emotional stimuli.

The function of the left MFG

The final lesion effect isolated in this task is that left MFG damage impairs interference resolution for negative stimuli. A close examination of the lesions in Patients O, P and Q indicate that they have damage to the left IFG/MFG in common. Patient O, whose lesion included the IFG, MFG, and a large area of the precentral gyrus including parts of the premotor cortex also showed longer reaction times and greater interference levels for all trial types. Based on the extent of Patient O's lesion we cannot determine whether the increase in RT results from damage to the premotor cortex or the left IFG; the shared behavior and lesion location of Patients O, P and Q do illustrate however that the left MFG has a critical role in interference resolution for negative stimuli. What the specific role of the IFG/MFG is in negative emotion interference resolution, is however not so clear. The MFG and IFG have been previously implicated as prefrontal brain regions that dissociate attention and emotion processing (Yamasaki, LaBar, McCarthy, 2002). In an fMRI study contrasting BOLD activation to attentional targets from BOLD activation to negative emotional distracters, Yamasaki and colleagues (2002) found that the MFG was activated by targets but deactivated by negative emotional distracters, whereas an anterior IFG region was activated by negative emotion distracters and relatively deactivated by targets. The authors conclude that a reciprocal relation between the MFG and the IFG may be a neural substrate for attention-emotion interactions. The present observed deficit of MFG lesion patients in negative emotion interference resolution supports this theory—damage to the MFG, damages one of the neural pathways that mediate attention and emotional distraction resulting in an inability to moderate the effects of irrelevant emotional information on interference resolution thereby selectively increasing negative emotional interference. We therefore postulate that the role of the left MFG is to mediate the relation between attention or task demands and the processing of distracting emotional content. Individuals with MFG damage were unable to use their MFG to focus on task demands and suppress the processing of irrelevant emotional content, resulting in greater interference for negative emotional stimuli.

One important question currently unanswered is the laterality and valence specificity of the left MFG finding. Unfortunately the distribution of participant's frontal lesions in the present dataset does not permit any conclusions regarding the laterality of the present findings—no right frontal lesion participants had damage in the same MFG area as participants O, P and Q. In regards to the valence specificity of the finding, it may be that the MFG mediates attentional control in particular to negative distracters—Yamasaki and colleagues used only negative emotion distracters in their investigation of the reciprocal relation between the MFG and IFG. Furthermore, research has also found that negative and positive emotion differentially capture attention (Strauss & Allen, 2009) suggesting that there may be valence specific attention neural mechanisms, and, that negative emotional content may capture attention more than positive emotional content (Carrette et al., 2001). The aforementioned findings suggest that MFG damage may result in an increased susceptibility to negative emotional distracters in particular. However, future research on MFG lesion laterality and valence in this and related emotional WM tasks is needed to draw more definitive conclusions.

Based on the lesion data from this study and an examination of the factors required to reduce interference for emotional stimuli, we propose a new neural model of emotion interference resolution facilitation that updates and expands upon the previous imaging study conducted by Levens and Phelps (2010). In this model, the amygdala sends arousal signals to the OFC,

anterior insula and surrounding cortices. These arousal/salience signals distinguish emotional information from neutral information which creates higher levels of familiarity that ramp-up interference for emotional information in the Recency-probes paradigm. Based on either arousal signals from the amygdala, or arousal signals generated within the OFC that temporally monitor arousal and emotional context, the right OFC generates an enhanced source recognition signal for emotional stimuli. This enhanced source signal is then sent to the anterior insula region. The insula then integrates the arousal/salience cues from the amygdala and the source signals from the OFC to enact a specific emotion interference resolution strategy that reduces interference for emotional stimuli. And finally the MFG mediates attention control to focus attention on task-relevant information and mitigate the effects of distracting task-irrelevant emotional information.

Alternate explanations for the findings

Although the neural model we present coherently accounts for the present data, additional explanations exist. For example, emotional information, aside from having valence and arousal properties is also a category. We speculate, based on how the Recency-probes paradigm places source recognition and familiarity in conflict, that it is the intrinsic emotional properties of the emotional stimulus (e.g. valence and arousal) that drive the facilitation of interference resolution, however, it may instead be the properties inherent in category membership. The additional context associated with category membership can also increase familiarity and enhance source recognition (Levens, Mutahtdie & Gotlib, 2009). Thus the semantic properties of a defined category, such as positive emotional stimuli, versus an ill-defined category, such as neutral stimuli, may also be what drove the behavioral results of this series of studies. If this is the case then the hippocampus and perirhinal cortex may play a role in the facilitation of interference resolution for emotional stimuli. The temporal lesion patients in this study have lesions that include the amygdala and partial sections of the hippocampus/entorhinal cortex, and perirhinal cortex. Furthermore the hippocampus and perirhinal cortex are involved in processing semantic knowledge and are critical for source memory encoding, specifically, item recollection and familiarity respectively (Bowles et al., 2010; Ford, Verfaellie & Giovanello, 2010; Tulving & Markowitsch, 1998; Gainotti, 2006). The hippocampus and perirhinal cortex therefore could be representing the source and familiarity semantic category information imbued in an emotion category, and interact with the OFC in a manner similar to the amygdala to create the enhanced source signal that reduces interference for emotional content.

One caveat to this interpretation is that the left temporal cortex lesions were primarily restricted to the amygdala and included only partial regions of the hippocampus, entorhinal, and perirhinal cortex. The smaller and more restricted lesion in the left temporal cortex lesions make the involvement of the hippocampus and perirhinal cortex less likely, however, the influence of category membership on emotional versus neutral stimuli may regardless play a role in creating the additional contextual cues that enhance source. The present findings are not able to dissociate the influence of category membership and the arousing properties of an emotional stimulus on interference resolution, especially since the valence and arousal properties of an emotional stimulus are what define the category of emotion. However, our neural model holds for either category or emotional stimulus property influences on interference resolution. Upon encountering an emotional word the amygdala is activated by the arousal properties of the emotional category or word and responds by sending arousal signals to the OFC. The OFC through temporal monitoring of the emotional category or word then translates the signal to include contextual details that enhance source. The anterior insula, involved in emotion processing and executive control (Wager and Barrett, 2004), integrates the neural signals from both the amygdala and OFC to enact a specific interference resolution strategy that reduces interference for emotional versus neutral

stimuli. And finally the MFG mediates attention control to focus attention on task-relevant information and mitigate the effects of distracting task-irrelevant emotional information.

In sum, our data from patients with focal temporal and frontal lesions clarify the roles likely played by the right OFC and left amygdala in the interference resolution of emotion specifically, and the integration of emotion into WM more broadly. The OFC and the amygdala work in conjunction to facilitate interference resolution: the amygdala provides an arousal signal that differentiates emotional from neutral stimuli, and the right OFC uses this arousal signal to create an enhanced emotional source signal. The left MFG mitigates the effects of distracting negative emotional content on task demands and the insula integrates salience and arousal signals from the amygdala and OFC to enact a specific emotion interference resolution strategy. While this study of the regions critical to emotion interference resolution facilitation provides a model of emotional interference resolution with designated roles for the OFC and amygdala, future research will need to clarify the role of the MFG and ascertain the role of the anterior insula. Nevertheless, the model proposed in this study elucidates that both the right OFC and left amygdala are critical to the integration of affect into WM, and may provide insight into what emotion and executive control impairments might underlie certain emotional regulation dysfunctions in psychiatric populations and following temporal and frontal lesions.

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Research Highlights

- Emotional information aids interference resolution in working memory
- Amygdala provides an arousal signal that enhances salience and differentiates emotional from neutral stimuli. This arousal/salience signal is sent to other emotion processing regions of the brain to facilitate processing of emotional stimuli in working memory
- The OFC, based on either the arousal signals from the amygdala, or on arousal signals generated within the OFC that temporally monitor arousal and emotional context, generates an enhanced source recognition signal for emotional stimuli in working memory

Neutral Condition			Delay	Probe	Trial Type	
Target set						
1.	sold	beard	mouse	+	beard	Yes-response
2.	mouse	ball	element	+	sweep	Non-interference trial
3.	travel	cold	tree	+	mouse	Interference trial
Emotional Condition						
1.	murder	bland	grow	+	murder	Yes-response
2.	board	terror	pain	+	kill	Non-interference trial
3.	truck	plant	terror	+	plant	Yes-response
4.	flour	slave	compute	+	terror	Interference trial

Figure 1.

Sample trials and trial types from the Neutral condition (all neutral words) and Emotion condition (neutral and emotional words). The emotion condition trials above are examples of Negative valence session trials. Positive valence session trials would show the same type of emotion word distribution throughout the trials, yet positive and neutral words would be used as stimuli. The trial types necessary for determining neutral interference resolution are shown in bold green font (Interference and Non-interference trials), while the trial types used for Emotion condition interference levels are shown in bold red font.

Figure 2.

Reconstruction of frontal and temporal lobe lesions based on MRI scans. The z-coordinates are indicated below each slice. Fourteen axial slices display the range of lesions across the patient groups. The patients are separated into four lesion location groups, (1) right frontal lobe, (2) left frontal lobe, (3) right temporal lobe and (4) left temporal lobe. The temporal lobe lesions include the amygdala and surrounding cortices. There are 5 right frontal lobe lesion, 7 patients left frontal lobe lesion, 5 right temporal lobe lesion, and 4 left temporal lobe lesion patients. The scale indicates the range of lesion overlap; dark orange indicates no lesion overlap and light yellow indicates a lesion location shared by 6 patients.

Figure 3.

Reconstruction of Patient J's and K's right frontal lobe lesions. The z- coordinates are indicated below each slice. The scale indicates the range of lesion overlap; Orange indicates no lesion overlap and white indicates a lesion location shared by both Patients J and K. Patient J's lesion extends dorsally to comprise the entire right PFC, yet Patient K's lesion is localized to the right OFC. The lesion overlap above indicates the only common location between patients J and K is the right OFC.

Figure 4.

Reconstruction of left temporal lobe lesions. The z- coordinates are indicated below each slice. The scale indicates the range of lesion overlap; dark orange indicates no lesion overlap and light yellow indicates a lesion location shared by all 4 patients. The lesion overlap above (see axial slices $z = -16$ and -20), indicates the amygdala has been removed in all 4 left temporal lesion patients.

Table 1

Subject Characteristics

Group	Hemisphere	n	age (yrs)	Sex (M/F)	Education (yrs)	IQ
Frontal	Right	5	39 (6)	2/2	15.4 (3)	110 (9)
	Left	7	39 (19)	3/5	15.3 (2)	112 (9)
Temporal	Right	5	47 (11)	2/3	16 (2)	113 (10)
	Left	4	47 (8)	2/2	16 (3)	111 (9)
Control		25	42 (11)	12/13	15.9 (3)	115 (10)

Note. Mean given with standard deviation in parentheses. Yrs = Years

Table 2

Stimuli Characteristics

	Arousal		Valence		Use Frequency		Word Type	
	M(SD)	Range	M(SD)	Range	M(SD)	Range	% Noun	
Neutral	3.9 (0.46)	2.9 – 5.3	5.2 (0.57)	3.8 – 7.3	31.5(32.4)	1 – 143	78%	
Positive	6.48* (0.62)	5.5 – 8.1	7.8* (0.43)	7.0 – 8.2	28.3(29.7)	1 – 173	73%	
Negative	6.58* (0.58)	4.59 – 8.2	2.25* (0.45)	1.25 – 3.23	24.5(37.2)	1 – 277	74%	

Note. Standard deviations are shown in parentheses. Word type is the percentage of words that qualify as nouns.

* Significant difference between neutral and emotional stimuli, $p < .01$.

Table 3

Reaction times and error rates for Controls and Patients.

		Negative valence session						Positive valence session									
		Neutral Condition			Emotion Condition			Facil Score		Neutral Condition			Emotion Condition			Facil Score	
		Non-inter	Inter	Int Score	Non-inter	Inter	Int Score		Non-inter	Inter	Int Score	Non-inter	Inter	Int Score			
Controls																	
RT		763 (174)	894 (198)	125 (53)	799 (193)	850 (191)	51 (70)	74 (79)	782 (178)	896 (205)	114 (75)	812 (193)	849 (197)	37 (62)	78 (68)		
ER		6% (7%)	6% (6%)		14% (5%)	7% (8%)			4% (4%)	5% (5%)		5% (6%)	9% (8%)				
All Lesion Patients																	
RT		798 (231)	923(273)	125 (71)	809(219)	924 (325)	116 (135)	9 (130)	794 (228)	916 (273)	122 (111)	847 (274)	906 (287)	59 (70)	62 (98)		
ER		1% (3%)	6% (8%)		12% (1%)	4% (10%)			0% (0%)	5% (7%)		1% (2%)	2% (5%)				
Right Temporal Resection Reaction Times																	
A		1212	1447	235	1208	1363	155	80	1176	1272	96	1328	1252	-76	172	Amg & Hipp	
B		606	701	95	722	771	49	46	561	639	78	631	653	22	56	Amg & Hipp	
C		866	1035	169	1038	1082	43	126	1006	1346	339	1037	1125	88	251	Amg & Hipp	
D		683	837	154	793	874	81	73	706	813	107	768	863	95	11	Amg & Hipp	
E		630	718	88	642	691	49	40	618	721	103	640	695	56	47	Amg & Hipp	
Left Temporal Resection Reaction Times																	
F		776	964	188	741	931	190	-2	964	924	-40	839	899	60	-100	Amg & Hipp	
G		651	719	68	674	747	73	-5	611	626	15	591	652	61	-46	Amg & Hipp	
H		733	827	94	757	842	85	9	726	747	21	807	830	24	-2	Amg & Hipp	
I		814	831	17	814	847	33	-16	704	807	104	706	812	106	-2	Amg & Hipp	
Right Frontal Resection Reaction Times																	
J		931	1075	143	816	1108	292	-149	862	910	48	953	1110	157	-109	OFC	
K		831	822	-9	674	849	174	-183	665	733	69	654	752	98	-30	PFC	
L		841	1098	257	867	989	122	135	914	983	69	917	947	30	39	Premotor cortex	
M		731	890	159	796	808	12	147	630	762	132	796	817	21	111	Dorsal MFG	
N		577	681	104	570	617	47	57	517	854	336	591	712	121	215	Dorsal PFC	
Left Frontal Resection Reaction Times																	
O		1546	1761	215	1485	2106	621	-406	1288	1667	379	1647	1880	233	146	MFG & IFG	

	Negative valence session										Positive valence session								
	Neutral Condition				Emotion Condition				Facil Score	Neutral Condition				Emotion Condition				Facil Score	
	Non-inter	Inter	Int Score	Non-inter	Inter	Int Score	Non-inter	Inter		Int Score	Non-inter	Inter	Int Score	Non-inter	Inter	Int Score			
P	824	852	28	729	857	127				815	848	33	833	844	11	22	MFG/SFG		
Q	567	648	82	573	684	111				591	761	170	591	702	111	59	OFC & ventral MFG		
R	916	1102	186	935	1002	66				1174	1303	129	1189	1176	-13	142	OFC & medial PFC		
S	630	783	153	632	698	66				659	873	213	735	801	66	148	Dorsal PFC		
T	559	630	71	628	605	-24				537	599	62	562	594	32	30	OFC & vIPFC		
U	829	955	126	886	938	52				957	1046	89	966	909	-57	146	Ventral OFC		

Note: Controls and lesion patients’ RTs and error rates for interference (Inter) and Non-interference (Non-Inter) trials in each condition as well as Interference scores (Int Score) and facilitation scores (Facil score) for each valence session. All RTs and error rates are rounded to the nearest whole number. Values in bold indicate outlier scores that differ by more than 2 standard deviations from those of controls. RT= reaction time; ER = error rate; AMG = amygdala; Hipp = Hippocampus; OFC = orbital frontal cortex; PFC = prefrontal cortex; MFG = medial frontal gyrus; IFG = inferior frontal gyrus; SFG = superior frontal gyrus; vIPFC = ventral lateral PFC.