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FN400 and LPC memory effects for concrete and abstract words

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Abstract

According to dual-process models, recognition memory depends on two neurocognitive mechanisms: familiarity, which has been linked to the frontal N400 (FN400) effect in studies using ERPs, and recollection, which is reflected by changes in the late positive complex (LPC). Recently, there has been some debate over the relationship between FN400 familiarity effects and N400 semantic effects. According to one view, these effects are one and the same. Proponents of this view have suggested that the frontal distribution of the FN400 could be due to stimulus concreteness: recognition memory experiments commonly use highly imageable or concrete words (or pictures), which elicit semantic ERPs with a frontal distribution. In the present study, we tested this claim using a recognition memory paradigm in which subjects memorized concrete and abstract nouns; half of the words changed font color between study and test. FN400 and LPC old/new effects were observed for abstract as well as concrete words, and were stronger over right hemisphere electrodes for concrete words. However, there was no difference in anteriority of the FN400 effect for the two word types. These findings challenge the notion that the frontal distribution of the FN400 old/new effect is fully explained by stimulus concreteness.

Descriptors: Memory, Language/speech, ERPs

Dual-process models assume the existence of two distinct processes in recognition memory—familiarity and recollection (Atkinson & Juola, 1974; Mandler, 1980; Yonelinas, 1999, 2002). Familiarity is fast-acting, automatic, and associated with a generic feeling that an item has previously been encountered. Recollection is slower and is accompanied by a more detailed memory for past events, such as when or where the item was previously encountered, or whether the item had a particular characteristic.

Studies in cognitive neuroscience have provided converging evidence for the dual process model (Aggleton et al., 2005; Rugg & Curran, 2007; Yonelinas, Otten, Shaw, & Rugg, 2005). In particular, ERPs have revealed neurophysiological indices of familiarity and recollection—the midfrontal FN400 and the parietal late positive complex (LPC)—which appear to be functionally as well as electrophysiologically distinct (Friedman & Johnson, 2000; Rugg & Curran, 2007; Tsivilis, Otten, & Rugg, 2001). In a study, Curran (2000) examined recognition memory for words that were inflected as singular (e.g., table) or plural (e.g., spoons). At test, old words (e.g., table, spoons), new words (e.g., forks), and plurality-reversed lures (e.g., tables, spoon) were presented. Subjects were instructed to classify as "studied" only the same-plurality old words. During the test phase, the FN400 component had a more negative amplitude for words that were correctly rejected (e.g., spoon or forks), as compared with those that were correctly recognized (e.g., table) as well as false alarms (e.g., tables). Because there was no difference in the FN400 response to correctly recognized items and false alarms, Curran (2000) concluded that the FN400 effect was due to familiarity-based memory, as opposed to recollection. By contrast, the LPC was recorded from 400–800 ms over parietal electrodes and was more positive in response to words that were correctly recognized, as compared with correct rejections and false alarms. Based on this pattern of results, the LPC was proposed as a specific index of recollection-based memory. In subsequent studies, ERP indices of familiarity and recollection were tested with regard to other characteristics of the stimuli used, such as picture orientation (Curran & Cleary, 2003; Nyhus & Curran, 2012) or color (Cycowicz, Friedman, & Snodgrass, 2001; Ecker, Zimmer, & Groh-Bordin, 2007a, 2007b; Groh-Bordin, Zimmer, & Ecker, 2006).

Paller, Voss, and Boehm (2007) challenged the claim that the FN400 component is a specific index of familiarity-based memory. Instead, they suggested that it could reflect conceptual-semantic processing. They argued that the repetition of stimuli between study and test phases in recognition memory experiments enhances the fluency of conceptual processing. This enhanced fluency is associated with electrophysiological responses that co-occur and contribute to the feeling of familiarity. Thus, the relative increase in FN400 negativity to correct rejections (i.e., correct responses to "new" stimuli) versus items perceived as "old" (i.e., hits and false

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alarms) might reflect the increased effort needed to retrieve their associated meanings, rather than the absence of familiarity-based memory. Conceptual-semantic processing of meaningful stimuli is indexed by the standard N400 potential, which was first described as having more pronounced, centroparietal negativity for semantic anomalies than for semantically congruent control sentences (Kutas & Hillyard, 1980). The N400 is attenuated when conceptual processing is facilitated, as in the case of repetition or conceptual priming (Kutas & Federmeier, 2011). If the account of Paller et al. (2007) is correct, then the so-called frontal N400, or FN400, effect could be regarded as functionally identical to the centroparietal N400 repetition effect. This proposal is reasonable, given that both ERPs occur within ∼300–500 ms after stimulus onset and that familiarity-based memory may be closely related to conceptual-semantic access (Paller et al., 2007). Electrophysiologically, one apparent difference is that the FN400 is typically maximal over midfrontal electrodes, whereas the classical semantic N400 is typically more posterior (Kutas & Hillyard, 1980). However, the spatial distribution of the N400 effect varies considerably across studies (Kutas & Federmeier, 2011). Therefore, it is possible that the frontal distribution of the FN400 reflects modulation of the semantic N400 by specific stimulus or task-related variables.

One well-known source of variation in N400 topography is stimulus concreteness: N400 priming effects are typically maximal over midfrontal, as opposed to parietal, sites for concrete words (Adorni & Proverbio, 2012; Kounios & Holcomb, 1994). Given this finding, Voss and Federmeier (2011) and others have argued that the frontal distribution of the FN400 might reflect the concreteness of word stimuli, rather than a process—such as familiarity-based memory—that can be dissociated from conceptual-semantic access. They suggested that concrete stimuli might facilitate semantic processing relative to abstract stimuli, thus shifting the N400 repetition effect for concrete stimuli toward frontal areas of the scalp. More generally, the variability in N400 topography is consistent with the view that the N400 is not a unitary component, but reflects the activation of multiple neural generators (Frishkoff, 2007; Frishkoff, Tucker, Davey, & Scherg, 2004; Kutas & Federmeier, 2011).

In the present study, we considered word concreteness and familiarity-based memory effects within the same paradigm. Previous studies of episodic memory effects have typically used words that are medium to high in concreteness. However, there are no reports of FN400 familiarity effects when comparing concrete versus abstract words. We suggest that word concreteness is not sufficient to account for the frontal distribution of the FN400 and that this effect might be also observed for abstract words. To test this idea, we used a modified version of Curran's (2000) experiments. Words appeared in different colored fonts in both the study and test phases. At test, participants were instructed to respond "old" only for items presented in the same color during the study and test phases. Importantly, words included abstract as well as concrete nouns. We hypothesized that frontal old/new effects would be elicited for both types of words from ∼300–500 ms. If the old/new effect for abstract words was found to be significant over frontal electrodes, this would challenge the claim that the anteriority of the FN400 is reducible to stimulus concreteness. We also compared the topographic distributions of old/new effects by concreteness level, using range normalization to rescale the difference waves prior to statistical analysis (Wilding, 2006). Any topographic differences between familiarity effects elicited by concrete and abstract words would indicate that stimulus concreteness can exert some influence on the FN400 topography. Finally, we expected to observe an LPC effect, that is, greater positivity for old responses versus new responses. We had no predictions regarding the influence of concreteness on the topography of the LPC.

Method

Participants

Thirty-four right-handed, native speakers of English (17 females, 17 males) participated in the experiment. The mean age of participants was $M = 23.0$ years ($SD = 3.14$; range = 18–29 years). All subjects had normal or corrected-to-normal vision, with no known neurological problems. Data from two subjects were excluded from the final analysis because there were too few good EEG trials (less than 36 in any category) after rejection of trials with electrophysiological artifacts. Therefore, final results are reported for 32 subjects (16 females, 16 males). All procedures were approved by University of Colorado Institutional Review Board. Subjects were paid $15 per hour or received course credit for their participation.

Materials and Procedure

Word stimuli. Stimuli included 864 words collected from the MRC Psycholinguistic Database (Wilson, 1988). Half of them were concrete nouns (concreteness ratings: $M = 570.69$, $SD = 34.15$, range = 501–670; imageability ratings: $M = 569.89$, $SD = 42.30$, range = 432–667; e.g., horse, bowl, chair). The other half were abstract nouns (concreteness ratings: $M = 305.40$, $SD = 28.30$, range = 217–349; imageability ratings: $M = 375.92$, $SD = 68.17$, range = 101–578; e.g., trouble, justice, origin). Concreteness was significantly different for concrete and abstract nouns, $t(862) = 124.31$, $p < .001$, and imageability also differed between the two word types, $t(862) = 50.25$, $p < .001$. There was no difference in written word frequency (Kučera & Francis, 1967) for concrete words ($M = 69.98$, $SD = 103.31$, range = 2–967) versus abstract words ($M = 81.79$, $SD = 129.12$, range = 1–683, $t(862) = 1.48$, $p = .14$. The two word types were balanced in length ($M = 5.32$, $SD = 1.22$, range = 3–7); that is, there were similar distributions of shorter (3-letter), midlength (4- to 5-letter), and longer (6- to 7-letter) words.

For the experiment, words were divided into 12 blocks of 72 words each, counterbalanced by concreteness and word length. Each block consisted of three subsets of 24 nouns (12 concrete, 12 abstract). The first subset was presented during study and test (old words). The second subset was presented only during test (new words). Finally, the third subset was presented in one font color during study and in a different font color at test (similar words). Half of the words within each subset (6 concrete, 6 abstract) were presented in blue (0, 114, 255 RGB values); the other half were presented in orange (255, 140, 0 RGB values). Half of the similar words changed from blue (in the study phase) to orange (in the test phase); the other half changed from orange to blue. The color manipulation was intended to approximate Curran's (2000) plurality manipulation without the restriction of using pluralizable words. The subsets were counterbalanced across subjects, such that each subset served equally as often as old, new, and similar within each block. Words were randomly ordered within each block, subject to the above constraints. An additional 48 words served as buffers: two were presented at the beginning and two were presented at the end of each study phase within each block. Another 36 nouns (half abstract, half concrete) were used as practice stimuli.

All stimuli were presented at the center of a 17-inch LCD computer monitor with a display resolution of 1,280 × 1,024 pixels and refresh rate of 60 Hz. Words were presented in Arial font, with a point size of 30.

Task procedure. Subjects were seated in a dimly lit, electrically shielded, acoustically isolated chamber, at a viewing distance of 50 cm from the computer monitor. Participants completed a short practice session, followed by 12 experimental (study–test) blocks.

In each study phase, 48 words (24 old and 24 similar) and four buffer words were presented (two in the beginning and two at the end of each list). At the beginning of each study trial, a fixation cross appeared for a random duration (between 1,400 and 1,600 ms) and was immediately followed by a word, which was presented for 1,000 ms. Subjects were instructed to study each word and to memorize its font color. No overt response was required during the study phase.

An old/new recognition test, or test phase, followed each study phase. Each of 72 test trials began with a fixation cross, which appeared for a random duration (between 1,400 and 1,600 ms) and was immediately replaced by a word, which was presented for 1,000 ms. The word was immediately followed by a response probe (a question mark, "?"). Subjects were asked to indicate whether the word was old (studied) or new. They were told to respond as quickly and accurately as possible, by pressing one of two buttons on the serial response box using their (right or left) index finger. They were also informed that they should answer "old" only in response to words that appeared in the same font color during the study and test phases; otherwise, they should respond "new." Assignment of left and right index fingers to old and new responses was counterbalanced across subjects. There were two subject-paced blink breaks during each test phase, one every 24 trials.

Subjects took self-paced breaks between the study and test phases and between blocks. Electrode impedances were checked before the start of the experiment and after every three blocks, lasting at least 5 min each time.

EEG Data Collection and Preprocessing

An EEG was recorded continuously from 128 scalp locations using a HydroCel Geodesic Sensor Net (Tucker, 1993) connected to a DC-coupled, 128-channel, high-input impedance amplifier (200 MΩ, NetAmps 200, Electrical Geodesics, Inc., Eugene, OR). The EEG was referenced to the vertex electrode, band-pass filtered (0.1–100 Hz), and digitized at a sampling rate of 250 Hz. Electrode impedances were kept below 50 kΩ, an acceptable range for this system.

NetStation (NetStation 4, Electrical Geodesics, Inc.) and EEGLAB version 13 (Delorme & Makeig, 2004) software was used for EEG signal processing and analysis. Continuous EEG was filtered offline, using a digital low-pass filter (40 Hz). The EEG was segmented into 1,200-ms epochs, beginning 200 ms prior to stimulus onset. Eye movements and eyeblinks were corrected using independent component analysis (ICA; Delorme, Sejnowski, & Makeig, 2007). Bad channels were manually marked as bad before ICA and interpolated after that using the spherical option of the EEGLAB function for channel interpolation (Bigdely-Shamlo, Mullen, Kothe, Su, & Robbins, 2015). Remaining artifacts were rejected using a moving window peak-to-peak amplitude method with window width 200 ms, window step 100 ms, and threshold ±100 μV (Luck, 2014). Artifact-free trials were averaged and

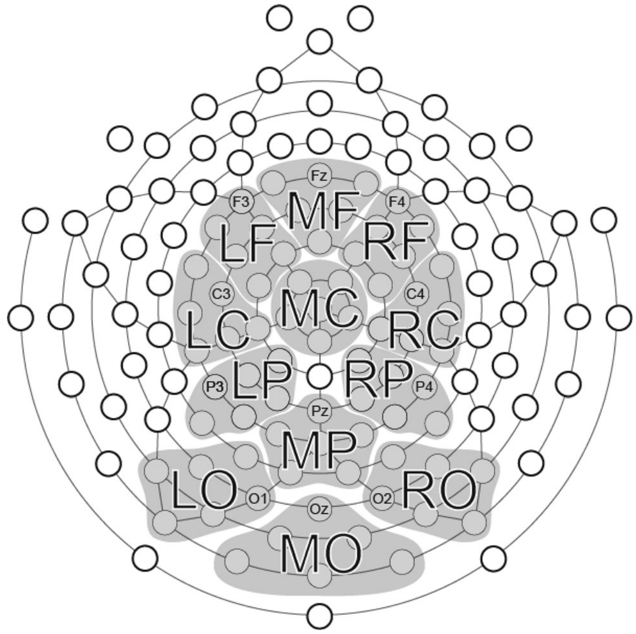

Figure 1. Sensor locations on the 128-channel HydroCel Geodesic Sensor Net. Twelve electrode clusters included in ANOVAs are denoted: LF = left frontal; MF = midline frontal; RF = right frontal; LC = left central; MC = midline central; RC = right central; LP = left parietal; MP = midline parietal; RP = right parietal; LO = left occipital; MO = midline occipital; RO = right occipital.

rereferenced to the average of all 128 channels. The resulting ERPs were baseline corrected relative to the 200-ms prestimulus interval.

The number of trials per subject was comparable across the four experimental conditions: (1) old responses to concrete words, collapsing across hits and false alarms ($M = 115.09$, $SD = 39.73$, range = 38–201); (2) old responses to abstract words, collapsing across hits and false alarms ($M = 111.28$, $SD = 40.26$, range = 36–185), (3) correct rejections of new concrete words ($M = 106.63$, $SD = 23.94$, range = 41–139), and (4) correct rejections of new abstract words ($M = 106.44$, $SD = 22.99$, range = 44–138).

Data Analysis

Behavioral data analysis. We compared the mean proportion of correct rejections, hits (correct recognition of old words), and false alarms (incorrect endorsement of color-changed words as old). Data were entered into a two-way repeated measures analysis of variance (ANOVA) with condition (correct rejection/hit/false alarm) and concreteness (concrete/abstract) as repeated measures. Greenhouse-Geisser corrected p values are reported where appropriate.

EEG data analysis. Our strategy for ERP analysis was similar to that of a previous study in which FN400 and N400 components were recorded (Stróżak, Abedzadeh, & Curran, 2016). We analyzed ERP data from twelve electrode clusters: left frontal, midline frontal, right frontal, left central, midline central, right central, left parietal, midline parietal, right parietal, left occipital, midline occipital, and right occipital. Each cluster consisted of six electrodes, including one International 10-20 channel (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, O1, Oz, or O2), and five adjacent electrodes (see Figure 1). Mean amplitude values were computed across the seven

Table 1. *Mean Proportions and Standard Errors of the Mean for Recognition Judgments*

	Correct rejection of new words		Correct recognition of old words		False recognition of similar words	
	M	*SEM*	*M*	*SEM*	*M*	*SEM*
Concrete	.85	.03	.58	.04	.32	.03
Abstract	.84	.03	.53	.03	.35	.03

electrodes within each region for both the FN400 (300–500 ms) and LPC (500–800 ms) time windows.

ERP analyses examined responses during the test phase of the experiment, focusing on old/new effects—that is, differences in response to studied words perceived as old (collapsing across hits to old words and false alarms to color-changed words) and words correctly perceived as new (i.e., correct rejections). We disregarded the accuracy of color judgments because there was little evidence that color-correct and color-incorrect old responses in our study indexed distinct neurocognitive processes.[1]

Separate analyses were conducted for midlatency (300–500 ms) and late (500–800 ms) time windows, corresponding to the FN400 and LPC effects. In each case, we conducted repeated measures ANOVAs with four factors: condition (old/new), concreteness (concrete/abstract), region (frontal/central/parietal/occipital), and laterality (left/midline/right). A Greenhouse-Geisser correction was applied when appropriate, and Bonferroni corrections were used to correct for multiple comparisons. Effects due to region and laterality are noted only if they interact with condition and/or concreteness.

Topographic analyses were conducted on rescaled data, using the range normalization procedure described in Wilding (2006). The vector-length procedure (McCarthy & Wood, 1985), though widely used, has been criticized for failing to address condition differences due to baseline effects and noise (Urbach & Kutas, 2002). According to Wilding (2006), the range normalization procedure is not susceptible to these criticisms.

Results presented below were obtained from average-referenced ERPs. The same analyses were conducted on mastoid-referenced ERPs (rereferencing to the average of the left and right mastoids) to allow for comparisons with results from other studies in which a mastoid reference was used (e.g., Bridger, Bader, Kriukova, Unger, & Mecklinger, 2012; Voss & Federmeier, 2011). The results of these analyses were consistent with the initial average-referenced analysis, so only average-reference results are reported.[2]

1. This was due to the fact that trials endorsed as false alarms were trials on which the word itself was correctly recognized, but for which only one specific detail (font color) was stated incorrectly. That allows a large amount of nonspecific recollection (not font-color related; e.g., contextual details) to remain in false alarms trials (we thank two anonymous reviewers for converging suggestions on this topic). Moreover, 300–500 ms ERPs for correct recognition and false alarms to similar lures were virtually identical, as is typically observed (e.g., Curran, 2000).

2. There were two reasons for not reporting mastoid-referenced data as the main results. First, for range-normalized topographic contrasts, there was greater error variance for mastoid-referenced data than for average-referenced data, as previously demonstrated by Dien (1998). This reduced the test statistics and resulted in nonsignificant Bonferroni-corrected post hoc p values for mastoid-referenced topographic interactions. Second, the average reference technique is preferable when analyzing the N400 potential because it produces topography that is more readily interpretable in terms of known physiology and anatomy in comparison to alternative references (Johnson & Hamm, 2000).

ERP waveform plots and topographic maps based on mastoid-referenced data are presented in the online supporting information Figure S1, S2, and S3.

Results

Behavioral Results

Mean proportions and standard errors of the mean for recognition judgments are summarized in Table 1. Analysis of mean accuracy revealed a main effect of condition, $F(2,62) = 61.76$, $p < .001$, $\eta^2 = .67$. Bonferroni-adjusted post hoc comparisons showed that participants were more accurate for correct rejections ($M = .85$, $SEM = .03$) versus hits ($M = .55$, $SEM = .04$; $p < .001$), and correct recognitions were more prevalent than false alarms ($M = .34$, $SEM = .03$; $p < .001$). A Condition $\times$ Concreteness interaction was also observed, $F(2,62) = 17.36$, $p < .001$, $\eta^2 = .36$. Bonferroni-corrected post hoc tests showed that subjects were more accurate in recognizing old concrete words ($M = .58$, $SEM = .04$) versus old abstract words ($M = .53$, $SEM = .03$; $p < .001$). Subjects were equally good at rejecting new concrete words ($M = .85$, $SEM = .03$) and new abstract words ($M = .84$, $SEM = .03$; $p = .59$). Also, the mean proportion of false alarms (to color-changed words) was larger for abstract words ($M = .35$, $SEM = .03$), as compared with concrete words ($M = .32$, $SEM = .03$; $p < .05$).

ERP Results

FN400 old/new effects (300–500 ms). Figure 2 and 3 show grand-averaged ERPs elicited during the test phase for each condition. Results for concrete nouns are depicted in Figure 2; results for abstract nouns are shown in Figure 3. In both figures, there appear to be differences in ERP responses to old versus new words in the FN400 (300–500 ms) and LPC (500–800 ms) windows.

Within the 300–500 ms time window, statistical analyses showed a main effect of condition, $F(1,31) = 26.57$, $p < .001$, $\eta^2 = .46$. ERPs were more negative for correct rejections ($M = -.14$ µV, $SEM = .09$) than for old responses ($M = .001$ µV, $SEM = .09$). The condition effect was clarified by Condition $\times$ Region, $F(1.63,50.66) = 10.59$, $p < .001$, $\eta^2 = .26$, and Condition $\times$ Region $\times$ Laterality, $F(3.42,106.14) = 6.17$, $p < .001$, $\eta^2 = .17$, interactions (see Figure 4A,B). Bonferroni-corrected post hoc comparisons for the Condition $\times$ Region interaction showed that the old/new effect was most pronounced in frontal ($p < .001$, $\eta^2 = .41$) and central ($p < .001$, $\eta^2 = .51$) regions, and was also significant in the parietal region ($p < .05$, $\eta^2 = .18$). The old/new effect was reversed in the occipital region, such that ERPs were more negative for old responses than for correct rejections ($p < .05$, $\eta^2 = .16$). Bonferroni-corrected post hoc comparisons for the Condition $\times$ Region $\times$ Laterality interaction showed that the old/new effect was most prominent in the midline central cluster ($p < .001$, $\eta^2 = .57$).

There was also a main effect of concreteness, $F(1,31) = 4.84$, $p < .05$, $\eta^2 = .14$. ERPs were more negative for concrete nouns ($M = -.10$ µV, $SEM = .10$) than for abstract nouns ($M = -.04$ µV, $SEM = .09$). The concreteness effect was clarified by Concreteness $\times$ Region, $F(1.5,46.6) = 29.7$, $p < .001$, $\eta^2 = .49$; Concreteness $\times$ Laterality, $F(2,62) = 5.19$, $p < .01$, $\eta^2 = .14$; and Concreteness $\times$ Region $\times$ Laterality, $F(4.2,130.14) = 10.34$, $p < .001$, $\eta^2 = .25$, interactions. Bonferroni-corrected post hoc comparisons for the Concreteness $\times$ Region interaction showed that ERPs to concrete words were more negative than ERPs to abstract words in frontal

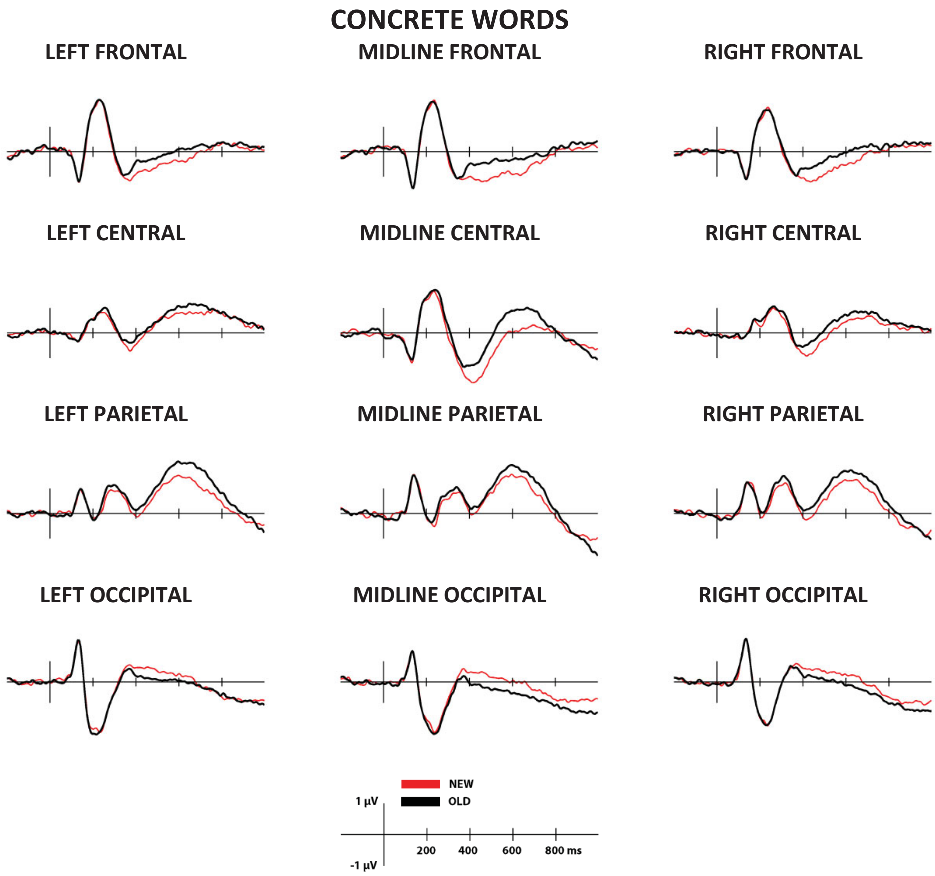

Figure 2. Grand-averaged ERPs for concrete words elicited by old responses (collapsed across hits and false alarms) and new responses (correct rejections).

($p < .001$, $\eta^2 = .50$) and central ($p < .001$, $\eta^2 = .53$) regions. The concreteness effect was reversed in occipital regions, such that ERPs were more negative for abstract versus concrete nouns ($p < .001$, $\eta^2 = .52$). Bonferroni-corrected post hoc comparisons for the Concreteness × Laterality interaction showed that ERPs to concrete words were more negative than ERPs to abstract words only in the right hemisphere ($p < .01$, $\eta^2 = .23$; $p = .62$ in the left hemisphere; $p = .065$ in the midline). Bonferroni-corrected post hoc comparisons for the Concreteness × Region × Laterality interaction showed that the concreteness effect was most prominent in the right frontal cluster ($p < .001$, $\eta^2 = .58$), in the midline central cluster ($p < .001$, $\eta^2 = .61$), and in the left occipital cluster ($p < .001$, $\eta^2 = .53$).

Importantly, there was no two-way Condition × Concreteness interaction, $F(1,31) = .004$, $p = .95$, $\eta^2 = .00$, and no three-way Condition × Concreteness × Region interaction, $F(1.47,45.49) = 1.49$, $p = .24$, $\eta^2 = .05$. Additional analyses were conducted, focusing on FN400 old/new effects for concrete and abstract words within the frontal region. Separate ANOVAs were conducted for concrete and abstract words, including ERPs in frontal regions only (i.e., data from left, midline, and right frontal clusters). Each analysis included two factors: condition (old/new) and laterality (left/midline/right). For concrete words, there was a main effect of condition, $F(1,31) = 18.22$, $p < .001$, $\eta^2 = .37$; ERPs were more negative for correct rejections ($M = -.92$ µV, $SEM = .23$) than for old responses ($M = -.56$ µV, $SEM = .26$). A main effect of condition was also observed for abstract words, $F(1,31) = 9.19$, $p < .01$, $\eta^2 = .23$; again, ERPs were more negative for correct rejections ($M = -.52$ µV, $SEM = .25$) than for old responses ($M = -.25$ µV, $SEM = .23$).

Topographic comparisons of FN400 effects for concrete and abstract words. Additional analyses were conducted, using range-normalized difference waves (Wilding, 2006), to evaluate topographic differences in old/new effects for concrete versus abstract nouns. The old/new difference wave for concrete nouns was created by subtracting correct rejections to concrete words from old responses to concrete words (collapsing across hits and false alarms). The old/new difference wave for abstract nouns was created following the same procedure. Topographic maps corresponding to the difference waves are depicted in Figure 4A,B. These figures show FN400 effects (i.e., increased positivity for old versus new responses from 300–500 ms) for abstract and concrete words.

Range-normalized data were entered into a repeated measures ANOVA, with three factors: contrast (old/new effect for concrete nouns vs. old/new effect for abstract nouns), region (frontal/central/parietal/occipital), and laterality (left/midline/right). Results showed a Contrast × Laterality interaction, $F(2,62) = 3.30$, $p < .05$, $\eta^2 = .10$. This interaction was deconstructed by conducting Bonferroni-corrected post hoc tests that compared old/new effects for concrete versus abstract words at each level of laterality (left

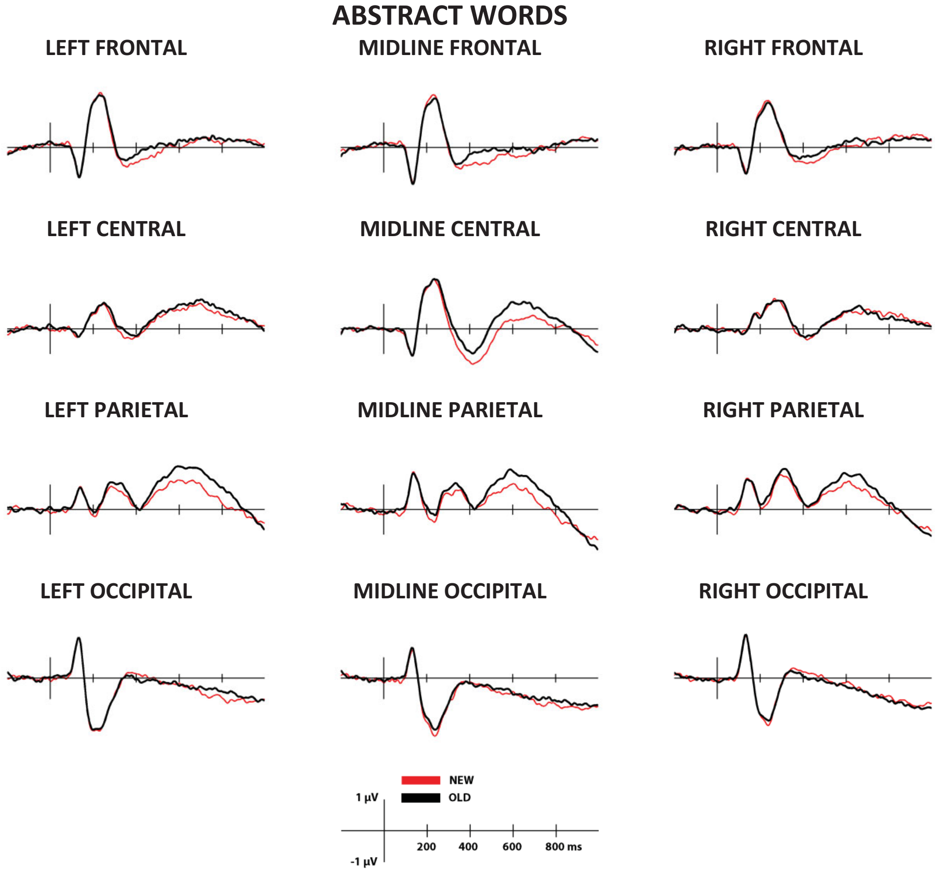

Figure 3. Grand-averaged ERPs for abstract words elicited by old responses (collapsed across hits and false alarms) and new responses (correct rejections).

hemisphere, midline, and right hemisphere clusters). Post hoc comparisons showed that the difference in the distribution of the old/new effects for concrete and abstract words was found only in the right hemisphere ($p < .05$); within this region, the old/new effect was larger for concrete than for abstract words. Importantly, there was no Contrast × Region interaction, $F(1.43,44.47) = .26$, $p = .70$, $\eta^2 = .008$, and no Contrast × Region × Laterality interaction, $F(4.21,130.59) = 1.3$, $p = .27$, $\eta^2 = .04$.

LPC old/new effects (500–800 ms). Within the 500–800 ms time window, there was a main effect of condition, $F(1,31) = 19.19$, $p < .001$, $\eta^2 = .38$. Consistent with previous studies, the LPC was more positive for old responses ($M = .41$ µV, $SEM = .10$) than for correct rejections ($M = .20$ µV, $SEM = .08$). The condition effect was clarified by a marginally significant Condition × Region interaction, $F(1.39,42.98) = 3.42$, $p = .058$, $\eta^2 = .10$, and by a significant Condition × Region × Laterality interaction, $F(3.68,114.20) = 4.68$, $p < .01$, $\eta^2 = .13$ (see Figure 4C,D). Bonferroni-corrected post hoc comparisons for the Condition × Region interaction showed that old responses elicited more positive ERPs than correct rejections within the central ($p < .01$, $\eta^2 = .29$) and parietal ($p < .01$, $\eta^2 = .29$) regions ($p = .057$ in frontal regions; $p = .37$ in occipital regions). Bonferroni-corrected post hoc comparisons for the Condition × Region × Laterality interaction showed that the old/new effect was most prominent within the midline central cluster ($p < .001$, $\eta^2 = .44$) and within the left parietal cluster ($p < .001$, $\eta^2 = .37$).

There was also a main effect of concreteness, $F(1,31) = 6.07$, $p < .05$, $\eta^2 = .16$. ERPs were more positive for concrete nouns ($M = .35$ µV, $SEM = .09$) than for abstract nouns ($M = .26$ µV, $SEM = .09$). The concreteness effect was clarified by a Concreteness × Region interaction, $F(1.68,52.16) = 17.88$, $p < .001$, $\eta^2 = .37$, and by a Concreteness × Region × Laterality interaction, $F(4.02,124.56) = 2.78$, $p < .05$, $\eta^2 = .08$. Bonferroni-corrected post hoc comparisons for the Concreteness × Region interaction showed that ERPs to concrete words were more negative than ERPs to abstract words in frontal regions ($p < .001$, $\eta^2 = .37$). This effect was reversed over posterior sites: concrete words elicited more positive ERPs than abstract words over parietal sites ($p < .01$, $\eta^2 = .29$) and also over occipital sites ($p < .001$, $\eta^2 = .40$). The concreteness effect was nonsignificant in central regions ($p = .17$). Bonferroni-corrected post hoc comparisons for the Concreteness × Region × Laterality interaction showed the most prominent concreteness effects within the right frontal cluster ($p < .001$, $\eta^2 = .38$), the midline parietal cluster ($p < .01$, $\eta^2 = .31$), and the right occipital cluster ($p < .001$, $\eta^2 = .43$).

Finally, a significant Condition × Concreteness × Region, $F(1.44,44.52) = 4.21$, $p < .05$, $\eta^2 = .12$, interaction was observed. For concrete words, Bonferroni-corrected post hoc comparisons revealed that old responses elicited more positive ERPs than correct rejections in frontal ($p < .05$, $\eta^2 = .16$), central ($p < .01$, $\eta^2 = .24$),

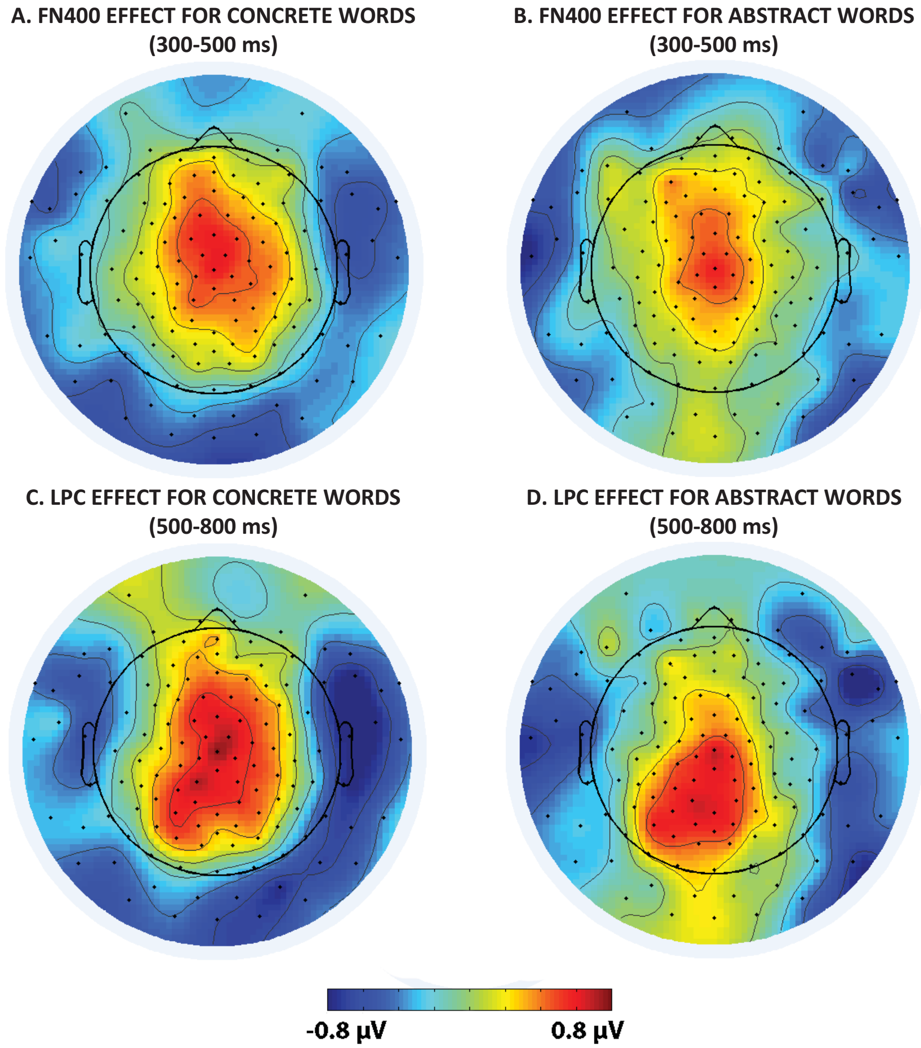

Figure 4. Topographic maps in the 300–500 ms time window for FN400 effect for concrete words (A), FN400 effect for abstract words (B), and in the 500–800 ms time window for LPC effect for concrete words (C), and LPC effect for abstract words (D)

and parietal ($p < .05$, $\eta^2 = .19$) regions. For abstract words, old responses elicited more positive ERPs than correct rejections within central ($p < .01$, $\eta^2 = .21$) and parietal ($p < .01$, $\eta^2 = .28$) regions, but the old/new effect for abstract words failed to reach significance within frontal regions ($p = .34$). For both word types, there was no difference in old versus new responses within occipital regions ($p = .07$ for concrete words; $p = .75$ for abstract words).

Topographic comparisons of LPC effects for concrete and abstract words. To further probe the topographic differences in LPC effects for concrete versus abstract words, we performed additional, unplanned comparisons using range-normalized difference waves (following Wilding, 2006), similar to the FN400 topographic comparisons. ERP difference waves for concrete and abstract words were computed within the LPC (500–800 ms) time window. The topographic maps corresponding to these difference waves are depicted in Figure 4C,D.

A repeated measures ANOVA was conducted, with three factors: contrast (old/new effect for concrete nouns vs. old/new effect for abstract words), region (frontal/central/parietal/occipital), and laterality (left/midline/right). Analysis of range-normalized data showed a significant Contrast × Laterality interaction, $F(2,62) = 3.48$, $p < .05$, $\eta^2 = .10$. This interaction was deconstructed by conducting Bonferroni-corrected post hoc tests that compared old/new effects for concrete versus abstract words at each level of laterality (left hemisphere, midline, right hemisphere). Post hoc comparisons showed that the difference in the distribution of the old/new effects for concrete and abstract words was significant only in the right hemisphere ($p < .05$), with larger old/new effects for concrete versus abstract words within this region. There was no Contrast × Region interaction, $F(1.33,41.27) = 1.99$, $p = .16$, $\eta^2 = .06$, and no Contrast × Region × Laterality interaction, $F(4.15,128.56) = 0.9$, $p = .47$, $\eta^2 = .03$.

Discussion

In the present study, our main goal was to compare the regional (i.e., frontal vs. nonfrontal) distribution of FN400 old/new effects for concrete and abstract words. Below, we discuss our findings for the FN400, as well as LPC effects and right hemisphere differences for concrete versus abstract words. We consider our findings with respect to prior work on episodic memory for meaningful stimuli (e.g., words, pictures). We also discuss how familiarity and conceptual-semantic processes may contribute to episodic memory for words. Finally, we discuss some limitations and suggestions for future studies.

The present study shows FN400 responses that are modulated by memory for recently presented words. ERP responses were more negative in response to new words that were correctly rejected than for words that were correctly or incorrectly endorsed as old within the FN400 (300–500 ms) time window, replicating the original findings of Curran (2000). Importantly, the FN400 memory effect was observed for abstract as well as concrete words, and there were no differences in regional distribution of the effect for the two word types. In addition, topographic analyses using range-normalized data (Wilding, 2006) failed to show any difference in regional distribution of the FN400 effect for concrete and abstract words. These findings are inconsistent with the claim that the anteriority of the FN400 is due to stimulus concreteness.

Although the FN400 old/new effects did not differ for concrete and abstract words, concrete words did elicit a more right-lateralized old/new memory effect (compare Figure 4A,B). This finding is significant for two reasons. First, it suggests that the topographic analysis had enough statistical power to detect interactions. Thus, the failure to observe an interaction between contrast (concrete vs. abstract old/new effect) and region (frontal, central, parietal, occipital) is unlikely due to the lack of statistical power. Second, the larger old/new effect for concrete versus abstract words within the right-lateral regions is consistent with previous ERP studies, which have shown larger responses for concrete versus abstract words over the right hemisphere (e.g., Kounios & Holcomb, 1994). Although it is risky to assume that right-lateral ERPs are due to underlying generators in the right cortex, researchers have noted that the right lateralization of concreteness effects are consistent with dual-coding theory (Holcomb, Kounios, Anderson, & West, 1999; West & Holcomb, 2000). According to this theory (Paivio, 1991), abstract words are represented using left hemisphere verbal codes, whereas concrete words also activate right hemisphere mechanisms that support imagery. On the other hand, Figure 4A,B shows that concrete words elicit a larger overall effect, as compared with abstract words. This finding is compatible with the context availability model, which suggests that concrete words activate more contextual information than abstract words and should therefore engage a larger set of brain areas (Fiebach & Friederici, 2004). In either case, the difference in old/new effects for concrete versus abstract words can inform our understanding of the FN400 potential.

With regard to the late positive complex, there is wide agreement that the LPC old/new effect is associated with recollection-based memory (Paller et al., 2007; Rugg & Curran, 2007). As expected, the present results indicated that LPC amplitudes were larger for old responses than for new responses. We also found that the LPC effect, like the FN400 effect, was more right lateralized for concrete than for abstract words and, in fact, was larger overall for concrete words. Thus, it seems that retrieval of detailed episodic information associated with concrete words activates more brain regions in the right hemisphere than the retrieval of such information associated with abstract words. Again, this finding may be consistent with dual-coding theory (Paivio, 1991) or context availability (Fiebach & Friederici, 2004), or both.

There is active debate about the functional significance of the FN400 effect. In particular, some researchers (e.g., Voss & Federmeier, 2011) have suggested that the FN400 old/new effect reflects the same set of cognitive processes as the N400 semantic effect. Indeed, given that both effects are elicited by meaningful stimuli—including pictures (Ganis, Kutas, & Sereno, 1996; Olivares, Iglesias, & Bobes, 1999) and words—it may be difficult to separate these two effects when subjects are engaged in semantic processing. In support of this idea, Stróżak and colleagues (2016) found that FN400 and N400 effects were topographically indistinguishable when semantic priming was embedded within a recognition test. However, when the semantic (study) and memory (test) phases were separated, the FN400 memory effect was found to have a more frontal distribution than the N400 semantic effect. This finding suggests that it may be possible to distinguish between FN400 familiarity and N400 semantic effects, even within the same experiment and in response to the same stimuli (also see Bridger et al., 2012).

Although the present results do not directly address differences between the view that the FN400 effects reflect familiarity (Groh-Bordin et al., 2006; Rugg & Curran, 2007) versus conceptual priming (Voss, Lucas, & Paller, 2010; Voss & Paller, 2007), they do suggest some ways to think about the interrelationship of these processes. Our finding that the FN400 old/new effect for concrete words was more right lateralized than for abstract words suggests that the electrophysiological underpinnings of familiarity judgments are not unitary, but vary according to the type of information being evaluated (here, concrete or abstract words). If so, familiarity might be explained in terms of fluency (or ease of processing) to prior stimulus exposure (Jacoby & Whitehouse, 1989), which would be more right lateralized for concrete than for abstract words because concrete concepts are represented more bilaterally than the abstract concepts. From this perspective, FN400 old/new effects could reflect familiarity or conceptual-semantic processing or both. This is also consistent with a finding of occipital familiarity-related ERPs for words that were orthographically, but not semantically similar to studied words (Lucas & Paller, 2013), which is compatible with the notion of representationally specific mechanisms of fluency that contributes to familiarity. Thus, it is possible that in our study, as well as in other recognition memory experiments, the FN400 and N400 components are intermixed and produce broad topography on the scalp.

It is important to acknowledge that conclusions based on the present findings may be limited in some respects. First, the task that we used in our procedure (remembering words and their font colors) is likely to have focused subjects' attention on nonsemantic (perceptual) features of the stimuli. It is therefore possible that our results would have been different if we had used a different task. Previous ERP studies have reported larger FN400 old/new effects following a semantic, as opposed to a perceptual, encoding task (Nyhus & Curran, 2009) and larger following deep than shallow encoding conditions (Rugg, Allan, & Birch, 2000). In line with this finding, participants in the present study had relatively low accuracy. It is also worth noting that participants made simple binary responses (old vs. new). It is therefore possible that the old/new contrast was contaminated by guesses based on font color, especially in the case of false alarms to color-altered words. In future studies, it may be possible to address this issue by using more fine-grained measures of episodic memory, such as confidence ratings, in addition to the old/new task.

Second, it is important to exercise caution when drawing inferences from null effects, such as the absence of interactions between old/new or concreteness effects and region, especially for the topographic comparisons. The range-normalization procedure that we used is more conservative than the alternative vector-length procedure and is therefore subject to Type II errors (Haig, Gordon, & Hook, 1997). However, we did observe a significant interaction between contrast (old/new effect for concrete words vs. old/new effect for abstract words) and laterality for this same analysis. This finding makes it less unlikely that the null finding is simply due to a lack of statistical power (also see Voss & Federmeier, 2011).

Finally, it should be acknowledged that amplitude rescaling (by whatever means) does not guarantee that topographic differences are driven by functional differences associated with experimental condition, rather than by nuisance factors, such as baseline differences or noise (Urbach & Kutas, 2006). Therefore, although we performed topographic analyses on amplitude-normalized data, using range-normalization procedure, the present findings should be replicated to minimize the possibility that topographic differences in the present study are due to chance factors. A few observations suggest that conditions were well matched at baseline within the present study and did not differ in terms of noise. For example, we did not observe any differences in the rate of rejection between concrete and abstract trials from the EEG analyses (see EEG data collection and preprocessing section for details). Thus, ERPs for concrete and abstract words were derived from roughly the same number of trials (although this does not guarantee that the signal-to-noise ratios are equivalent). Moreover, the directionality of the observed effects—including larger differences for concrete versus abstract words in right-lateral areas—is consistent with previous findings. Nonetheless, future studies should aim to replicate these findings and to explore other factors, such as task and ease of stimulus encoding and recall, to clarify the cognitive bases of these effects.

In conclusion, we observed FN400 and LPC old/new effects for abstract as well as concrete words. Both effects were stronger over right hemisphere electrodes in response to concrete versus abstract words, consistent with dual-coding theory (Paivio, 1991). However, it is also important to note that concrete words elicited larger overall effects, which could be explained by activation of additional contextual information (including more semantic features), as hypothesized by the context availability model (Fiebach & Friederici, 2004). Importantly, there was no difference in anteriority of the FN400 effect for concrete and abstract words. This finding suggests that the frontal distribution of the FN400 old/new effect does not merely reflect an anterior shift of the semantic N400 due to stimulus concreteness (Voss & Federmeier, 2011).

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Supporting Information

Additional supporting information may be found in the online version of this article:

Figure S1: Mastoid-referenced grand-averaged ERPs for concrete words elicited by old responses and new responses.

Figure S2: Mastoid-referenced grand-averaged ERPs for abstract words elicited by old responses and new responses.

Figure S3: Mastoid-referenced topographic maps for FN400 and LPC effects for concrete words and abstract words.