How word frequency modulates masked repetition priming: An ERP investigation

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Abstract

The present study used event-related potentials (ERPs) to provide precise temporal information about the modulation of masked repetition priming effects × word frequency during the course of target word recognition. Contrary to the pattern seen with behavioral response times in prior research, we predicted that high-frequency words should generate larger and earlier peaking repetition priming effects than low-frequency words in the N400 time window. This prediction was supported by the results of two experiments. Furthermore, repetition priming effects in the N250 time window were found for low-frequency words in both experiments, whereas for high-frequency words these effects were seen only at the shorter (50 ms stimulus onset asynchrony [SOA]) used in Experiment 2, and not in Experiment 1 (70 ms SOA). We explain this pattern as resulting from reset mechanisms operating on the form representations activated by prime stimuli when primes and targets are processed as separate perceptual events.

Descriptors: Masked priming, ERPs, Word frequency, Repetition, Sigmoid activation function

Much research has demonstrated that reactions to a stimulus can be influenced by prior exposure to the same or a related stimulus. For example, in the case of word stimuli it has been shown that preceding a target word by a prime stimulus that is the same word results in faster reaction times and increased accuracy in identifying the target when compared to the situation where primes are unrelated to targets (e.g., Forster & Davis, 1984; Scarborough, Cortese, & Scarborough, 1977). One interesting characteristic of these repetition priming effects is that they can be induced even if the observer is not aware of the prime stimulus. So-called "masked priming" has been extensively used as a means to study early word processing mechanisms (Forster, 1998).

In a masked repetition priming experiment with printed word stimuli, participants are typically asked to make a lexical decision response to a clearly visible target stimulus—a string of letters that can either be a real word or a string of letters that is not a word of the language under study (a nonword). Prior to the presentation of the visible target, and unbeknownst to participants, a prime stimulus is presented very briefly. Masking, along with brief presentation durations, makes the prime undetectable by viewers. This prime stimulus can either be the same as the target or a different stimulus, and the difference in performance (response times and error rates) to target stimuli as a function of the nature of the prime stimulus determines the size of the repetition effect. A substantial body of research has shown that when a masked prime word is followed by the same word as a visible target, lexical decision responses to word targets are faster and more accurate compared to when the prime and target are unrelated words (e.g., Forster & Davis, 1984; Segui & Grainger, 1990). This is known as the masked repetition priming effect.

The general theoretical framework of the interactive-activation model of visual word recognition (McClelland & Rumelhart, 1981) provides a straightforward account of masked repetition priming effects. Within this framework, upon presentation of a word stimulus, activation builds up over time in letter and word detectors, with letter-level activation being fed by feature-level processing, and word-level activation fed by activation at the letter level. This build-up of activation continues, as long as the stimulus is present, until a criterion level of activation is reached and the stimulus word is identified (Grainger & Jacobs, 1996; Jacobs & Grainger, 1992). Stimuli that are presented too briefly do not generate sufficient activation to reach such criterion levels, and therefore remain unidentified. More critically, activation can accumulate across stimuli that immediately follow each other, as long as the first stimulus (the prime) is presented sufficiently briefly to prevent the triggering of a reset of activation from one trial to the other (Grainger & Jacobs, 1999). This reset mechanism is thought to concern only form-level representations (i.e., orthographic and phonological representations for word stimuli) that would otherwise interfere with processing of the new stimulus (Holcomb & Grainger, 2007). Masked repetition priming effects that are driven by activity in form-level representations can therefore only arise when there is no reset
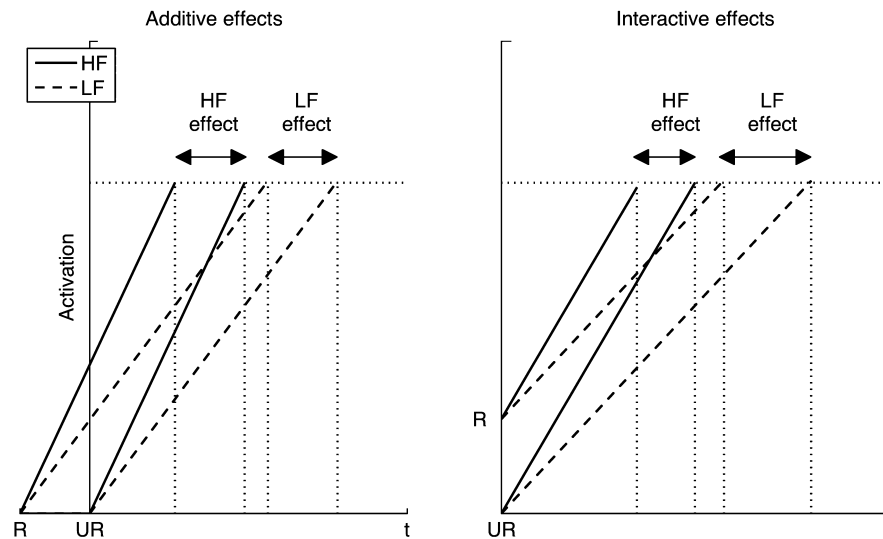
Figure 1. Illustration of how additive (left panel) or interactive (right panel) effects of Frequency and Repetition can be obtained in behavioral response latencies. Activation of the lexical representation corresponding to the target word rises faster for high-frequency (HF) words than low-frequency (LF) words, and a behavioral response is triggered whenever the activation value of a lexical representation reaches a criterion level. Priming effects are simulated by a higher activation level in the target word representation upon presentation of the target in the repetition condition (R) compared with the unrelated condition (UR). This initial advantage is greater for high-frequency words than low-frequency words in the left panel, and the same for both word frequencies in the right panel. The resulting repetition priming effect sizes are shown for low-frequency and high-frequency words.

between prime and target stimuli such that the activation generated during prime processing is maintained upon presentation of the target stimulus. With prime durations that are long enough to trigger a reset, masked repetition priming effects can still arise via activity in semantic representations that are shared by prime and target stimuli (Holcomb & Grainger, 2007). Whether or not the prime and target are the same word determines the compatibility of prime-generated activity at different levels of processing with the activity generated by the target stimulus, and therefore whether or not target processing will be facilitated (see Jacobs & Grainger, 1992, for simulations of masked repetition priming with the interactive-activation model).

How might word frequency affect masked repetition priming? Many would agree that word frequency determines the rate of accumulation of information from a word stimulus (e.g., Ratcliff, Gomez, & McKoon, 2004) and therefore the speed with which activation builds up in lexical representations (via, e.g., greater connection strengths between letter and word representations for high-frequency words).[1] Intuitively, one might therefore expect high-frequency words to benefit more from a masked repetition prime than low-frequency words, under the assumption that a high-frequency prime will generate higher levels of activation in lexical representations than a low-frequency prime when stimulus processing time is limited by the brief prime duration and subsequent backward mask. Put simply, if what differentiates high-frequency words from low-frequency words is the rate of accumulation of information in lexical representations, then more information should have accumulated after presentation of a high-frequency

prime than a low-frequency prime, causing greater priming effects. A more formal analysis will show, however, that this is not necessarily the case when priming effects are measured at the end point of processing via a behavioral response.

Figure 1 provides a schematic description of a simple information accumulation model with a response criterion for a behavioral response set on lexical activation (such as for generating a "word" response in the lexical decision task, Grainger & Jacobs, 1996). The idea is that information accumulates in lexical representations over time until a critical activation level is reached and a behavioral response is triggered. On the left side of Figure 1, we describe a scenario in which there is complete integration of information across prime and target in the repetition condition. In this case, the gain in processing time when primes are the same word as targets is equal to the prime duration, which is of course the same for high-frequency and low-frequency words. Repetition priming is therefore additive with word frequency under these conditions (i.e., the same amount of priming is obtained for high-frequency and low-frequency words). Figure 1 also illustrates conditions in which interactive effects of word frequency and masked repetition priming can be obtained (on the right side of the figure). Within the framework of our simple linear accumulator model, this arises when the initial priming benefit is the same for high-frequency and low-frequency words. This would occur when prime stimuli mostly affect activity in sublexical representations, and do so independently of prime word frequency. In this case, both low-frequency and high-frequency words would benefit from the same advantage in the repetition condition, but given the slower rise in activation associated with low-frequency words, this generates greater repetition effects for these words in terms of the time to reach the response criterion (i.e., interactive effects of Frequency and Repetition).

Given these two possibilities, it is reassuring to note that behavioral priming effects reported in the literature all show either one of these two predicted patterns. That is, either additive effects of

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1. In the original interactive-activation model (McClelland & Rumelhart, 1981), word frequency was implemented via changes in the resting-level activation of word representations. This is best thought of as a computational convenience compared with the more neurobiologically plausible implementation of frequency-dependent modifications in connection strengths, used in other connectionist models.
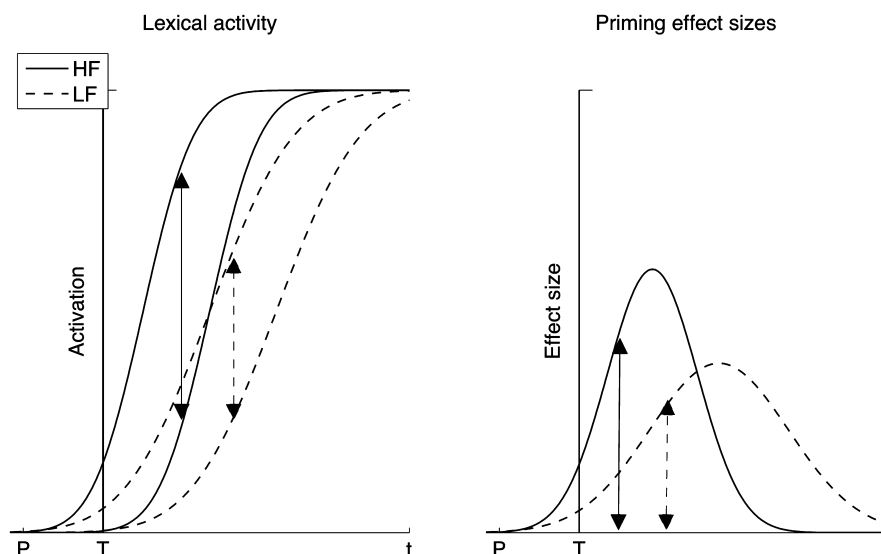
Figure 2. Illustration of how effects of repetition priming vary with time (t) when accumulation of lexical activity is modeled as a sigmoid activation function. Left panel shows sigmoid activation functions of lexical activity generated by high-frequency (HF) and low-frequency (LF) words in repetition (activation starts accumulating upon prime presentation [P]) and unrelated prime conditions (activation starts accumulating upon target presentation [T]). Right panel shows the variation in priming effect sizes (difference in activation level across the repetition and unrelated conditions) over time for high-frequency and low-frequency words (see examples shown by bidirectional arrows). Note that T represents the moment in time that activity in the lexical representation of the target word begins to rise after target word presentation, and does not represent target onset.

Frequency and Repetition, with statistically equivalent priming effects for low-frequency and high-frequency words (e.g., Forster & Davis, 1984; Kinoshita, 2006; Segui & Grainger, 1990), or interactive effects, with greater priming for low-frequency words (e.g., Bodner & Masson, 2001; Kinoshita, 2006; Kliegl, Masson, & Richter, 2010).[2] To our knowledge, the opposite pattern of statistically greater priming from high-frequency words has not been reported. Thus, summing up prior behavioral research, we can therefore conclude that, if anything, the masked repetition priming effect is greater for low-frequency words than high-frequency words, and certainly never the opposite (see Kinoshita, 2006, for a review).

Let us now consider possible differences in masked repetition priming for high-frequency and low-frequency words during the course of target word processing. When considering the effects of a given variable prior to reaching some criterion level of activation for response generation, the precise form of activation functions becomes critical (note that this is not the case for the predictions derived from the models shown in Figure 1, which do not depend on the precise form of activation functions). Figure 2 provides an illustration with standard sigmoid activation functions that are typically used in neural network modeling to describe changes in activity over time at the level of neural populations (Wilson & Cowan, 1972; see Marreiros, Daunizeau, Kiebel, & Friston, 2008, for a recent investigation). In the example shown in Figure 2, we assume perfect integration of information across prime and target

(as in the left panel of Figure 1), but having partial integration of information would not qualitatively change the predictions.

What we can see in Figure 2 is that, as activation starts to rise in lexical representations following target word presentation, there is a period of time where the difference in activation in the repetition and unrelated prime conditions is larger for high-frequency words compared with low-frequency words. We therefore have a situation where interactive effects of Repetition and Frequency should be observed, but this time with greater priming effects for high-frequency than low-frequency words. As activation accumulates over time, the size of the low-frequency priming effect will grow and eventually become greater than the high-frequency effect, with a later peak in its maximum size as shown in the right panel of Figure 2.

According to this analysis, if one were to have a measure of lexical processing during the course of word recognition, by measuring event-related potentials (ERPs) for example, then one ought to be able to observe stronger repetition priming effects for high-frequency words than low-frequency words. This priming advantage for high-frequency targets compared with low-frequency targets should start to be visible as soon as ERPs begin to reflect activity in whole-word representations (this is the activity that is simulated in Figure 2). Prior to this point in time, repetition priming effects in the ERP waveforms should mostly reflect sublexical processing, and therefore be relatively independent of word frequency (barring possible top-down influences). Sublexical processing is not simulated in Figures 1 and 2, and constitutes all processing prior to the initial build-up of activation in lexical representations (e.g., in letter representations).

Given these predictions, the current study provides an important extension of prior work investigating effects of word frequency and masked repetition priming, by recording ERPs while participants silently read words for meaning. ERPs, which are a continuous measure of the electrical activity of the brain, have been shown to

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2. Bodner and Masson (2001) and Kinoshita (2006) have suggested that the reason interactive effects emerge in certain experiments and not others is due to stimulus selection criteria. For interactive effects to emerge, target words must be of sufficiently high frequency in the high-frequency condition, and the low-frequency words must be known to participants. We will not dwell further on this point, since whether or not behavioral effects are interactive or additive is irrelevant for the present purposes.
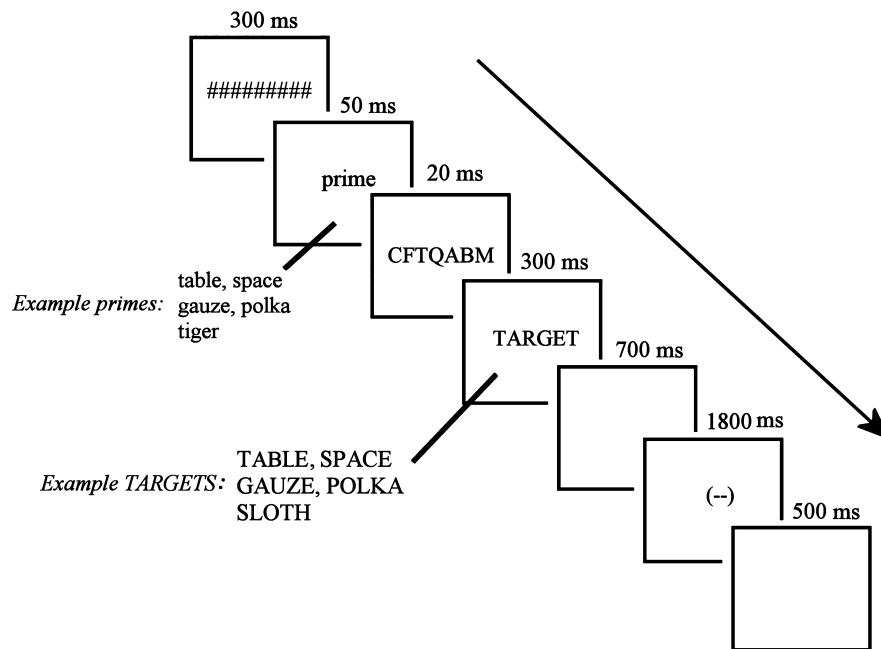
300 ms

######### 50 ms

prime 20 ms

CFTQABM 300 ms

TARGET 700 ms

1800 ms

(--) 500 ms

Example primes: table, space gauze, polka tiger

Example TARGETS: TABLE, SPACE GAUZE, POLKA SLOTH

Figure 3. Schematic of sequence of events on a typical trial and examples of prime and target stimuli in the four experimental conditions.

be sensitive to sensory, perceptual, and cognitive processes (for a review, see Luck, 2005). In recent research combining ERP recordings with the masked priming technique, we have begun to link specific ERP components that are modulated by a particular priming manipulation to the underlying processing thought to be driving the ERP effect. This hypothetical mapping of ERP components onto underlying processes has been performed within the framework of a model of visual word recognition that describes the component processes involved in mapping visual features onto semantic representations via sublexical and lexical form representations (Grainger & Holcomb, 2009; Holcomb & Grainger, 2006; 2007; Kiyonaga, Grainger, Midgley, & Holcomb, 2007).

The two ERP components that are relevant to the current study are the N250 and N400. These are two negative components, peaking at around 250 ms and 400 ms posttarget onset, whose amplitudes have been found to be sensitive to masked priming. Our prior research has repeatedly revealed robust effects of masked repetition priming on both of these components, with larger negativities for unrelated than repeated words. (Holcomb & Grainger, 2006, 2007; Kiyonaga et al., 2007; see Grainger & Holcomb, 2009, for a review). In our prior work, we have proposed that the N250 component reflects the bulk of activity in sublexical representations, as they receive information from lower levels and send forward information to whole-word (lexical) form representations. The N400, on the other hand, is thought to reflect activity related to the mapping of whole-word form representations onto semantic representations, at least in experiments using single words rather than sentences. Although the results of prior research suggest that feedback from frequency-sensitive whole-word representations can influence N250 amplitude (e.g., Massol, Midgley, Holcomb, & Grainger 2011; Midgley, Holcomb, & Grainger, 2009; Morris, Franck, Grainger, & Holcomb, 2007), the bulk of such lexical influences is expected to be seen in the beginning of the N400 time window.

Summing up, the key predictions for the present study are as follows: (a) Early sublexical repetition priming effects should be the same for high-frequency and low-frequency words, and this pattern of priming effects should be seen in the N250 ERP component; and (b) Repetition priming effects that reflect activation at the level of whole-word representations should be mostly visible in the N400 ERP component, and these priming effects should be stronger and peak earlier for high-frequency words than low-frequency words. To test these predictions, we measured the ERPs generated by target words in two masked repetition priming experiments with low-frequency and high-frequency words. Both experiments used the now standard ERP masked priming paradigm where ERPs were recorded on each trial to a series of visual stimuli displayed in rapid succession (see Grainger & Holcomb, 2009, for a review of the current literature using this paradigm). In Experiment 1, these included a forward mask consisting of a row of hash marks presented for 300 ms, a prime word presented in all lowercase letters for 50 ms, a backward mask consisting of a row of consonant strings for 20 ms, and a target word in all uppercase letters for 300 ms (see Figure 3). Experiment 2 used the same materials and experimental design as Experiment 1, but decreased the amount of time between the onset of prime and target words by removing the consonant string stimulus and using the target word itself as a backward mask (note that this is possible because the prime and target are in different cases).

Experiment 1

Methods

Participants. Twenty-four native English speaking Tufts University students (10 male, mean age = 20.2 years) were recruited and received compensation for their participation. All were right-handed, and had normal or corrected-to-normal visual acuity with no history of neurological insult or language disability. All participants reported that they learned no other language before the age of five.

Stimuli. The critical stimuli for this study were 120 words of which 60 were low-frequency items (mean log HAL frequency = 5.83, range 4.14–7.03) and 60 were high-frequency words (mean log HAL frequency = 11.06, range 9.3–13.7; English Lexicon Project: Balota et al., 2007). We also had all 120 words and an additional 60 low-frequency filler words rated for familiarity by a comparable group of 15 Tufts undergraduates. Participants were instructed that a rating of 5 should be used for words that were very familiar, and a rating of 1 was to be used for words they did not know. The 60 high-frequency words were rated as highly familiar with an average rating of 4.93 (range 4.43–5.0) and the 60 low-frequency words were rated as significantly less familiar with a mean of 3.53 (range 1.644–4.64, $t(59) = 14.25$, $p < .0001$). Importantly, fewer than 5% of the 900 ratings of low-frequency words were in the "don't know" category, and all words were rated as being known by at least 60% of the participants.

Both types of items were arranged in pairs; the first member of each pair was referred to as the prime and the second member as the target. From these pairs, three stimulus lists were formed. There were four stimulus conditions in each list: repeated high-frequency, unrelated high-frequency, repeated low-frequency, and unrelated low-frequency. The repeated condition refers to trials where the target was a full repetition of the prime (e.g., table–TABLE), and the unrelated condition refers to trials where the prime and target were unrelated words (e.g., space–TABLE). Each list was subdivided into 3 blocks of 20 items per condition. Across blocks each target word appeared once in each of the repeated (prime and target), unrelated prime, and unrelated target conditions, but no item was presented on more than one trial within a block as either a target or a prime. For example, if the word TABLE appeared in the repetition condition of block 1, it would not appear again until the second block where it would be presented as an unrelated prime and then once more as an unrelated target in block 3. For another item like SPACE, it would appear first as an unrelated target in block 1, as an unrelated prime in block 2, and as a related target in block 3. In this way, across the experiment, each participant saw each target word in the repeated and the unrelated conditions, and unrelated primes were re-pairings of repetition primes, which assures that average ERPs in the repetition and unrelated prime conditions are formed from exactly the same items (for both primes and targets) within participants. And because items were explicitly repeated within participants only after a long lag (on average after 90 trials), there is likely to be little effect of explicit episodic repetition effects (Misra & Holcomb, 2003).

Each list also contained 60 trials where an animal probe name appeared in target position and 15 trials where an animal probe appeared in the prime position (mean log HAL frequency = 6.84, range 10.5–2.2). On probe trials, half of the time a high-frequency nonanimal filler word was paired with the animal name and the other half a low-frequency word was paired. Animal probes were used as go items in a go/no-go semantic categorization task in which participants were instructed to rapidly press a single button with their right thumb whenever they detected an animal name. Participants were told to read all other words passively without responding (i.e., critical stimuli did not require an overt response). The 15 probe items appearing in the prime position served as a measure of prime detectability, thus providing an objective measure of the effectiveness of the masking procedure. Prior to the experimental run, a practice block was run to familiarize the participant with the procedure.

Procedure. All stimuli were presented in the center of a 19-inch monitor set to a refresh rate of 100 Hz and located approximately 125 cm directly in front of the participant. Stimuli were displayed as white letters on a black background in Arial font. Each trial began with a forward mask of 9 hash marks (#########) presented for a duration of 300 ms. The mask was immediately replaced at the same location on the screen by the prime word in lowercase letters (e.g., table) and was displayed for 50 ms. The prime was then immediately replaced by a 20 ms backward mask of an uppercase consonant string of seven letters (e.g., CFTQABM), which was in turn replaced by a 200 ms target word (e.g., TABLE) in capital letters. All target words were followed by a 700 ms blank screen, which was replaced by a blink stimulus (Figure 3). Participants were instructed to blink only during the 1800 ms that this stimulus was on the screen. The blink stimulus was followed by a blank screen for 500 ms, after which the next trial began.

EEG recording procedure. Participants were seated in a comfortable chair in a sound attenuated darkened room. An electro-cap fitted with tin electrodes was used to record continuous electroencephalogram (EEG) from 29 sites on the scalp including sites over left and right frontal-polar (FP1/FP2), frontal (F3/F4, F7/F8), frontal-central (FC1/FC2, FC5/FC6), central (C3/C4), temporal (T5/T6, T3/T4), central-parietal (CP1/CP2, CP5/CP6), parietal (P3/P4), and occipital (O1/O2) areas and five midline sites over the frontal-polar (FPz), frontal (Fz), central (Cz), parietal (Pz), and occipital (Oz) areas (see Figure 4). Four additional electrodes were attached: one below the left eye (to monitor for vertical eye movement/blinks), one to the right of the right eye (to monitor for horizontal eye movements), one over the left mastoid (reference), and one over the right mastoid (recorded actively to monitor for differential mastoid activity). All EEG electrode impedances were maintained below 5 kΩ (impedance for eye electrodes was less than 10 kΩ). The EEG was amplified by an SA Bioamplifier with a bandpass of 0.01 and 40 Hz, and the EEGs were continuously
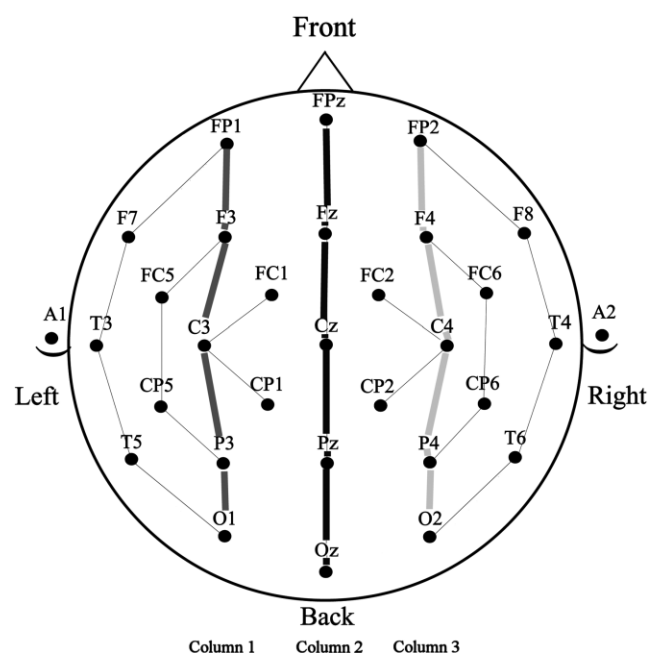

Figure 4. Electrode montage and three analysis columns used for ANOVAs.

sampled at a rate of 250 Hz. Trials with blinks and eye movement artifacts were rejected before averaging.

Data analysis. Separate compound ERPs (i.e., reflecting a combination of prime and target activity) from the four critical prime-target conditions (high-frequency repeated, high-frequency unrelated, low-frequency repeated, and low-frequency unrelated) were calculated by averaging 1024 ms of EEG activity starting 100 ms pretarget onset at each of the 32 electrode sites. These ERPs were then baselined to the average of the 100 ms pretarget period and low-pass filtered at 15 Hz. Only trials without muscle artifact or eye movement/blink activity (less than 10% of trials were rejected in both experiments) were included in the averages. We inspected the average activity at the right mastoid across the four conditions of interest to determine if differential mastoid activity necessitated rereferencing to the average of the two mastoids. No such activity was noted, so the data from the left mastoid reference was used for subsequent analysis. Mean amplitudes in two temporal windows similar to those used in several previous masked prime experiments were used to quantify the ERPs in the four conditions: 150–275 ms for the N250 and 375–500 ms for the N400 (Grainger, Kiyonaga, & Holcomb, 2006; Holcomb & Grainger, 2006). Repeated measures analyses of variance (ANOVAs) with within-subject factors of frequency (low vs. high) and repetition (repeated vs. unrelated) as well as hemisphere (left, midline, left) and anterior-posterior electrode position were used to analyze the ERP data. Specifically for the anterior-posterior electrode factor, five electrode sites in Column 1 (FP1, F3, C3, P3, O2), Column 2 (FPz, Fz, Cz, Pz, Oz), and Column 3 (FP2, F4, C4, P4, O2) were chosen for analyses. This provided ANOVA factors of hemisphere (left, middle, right) and anterior-posterior position (most anterior 1 vs. most posterior 5—see Figure 3). Follow-up ANOVAs were performed for high-frequency and low-frequency words separately including the factors of repetition, hemisphere, and anterior-posterior position (as described above). For all statistical analyses, Geisser-Greenhouse correction was used for all repeated measures factors with greater than 2 degrees of freedom in the numerator (Geisser & Greenhouse, 1959).

Results

Behavioral results. Participants detected an average of 90% of the animal probe words in the target position ($d' = 3.07$) and 11% in the prime position ($d' = .61$).

Event-related potentials. Grand-average ERPs time-locked to target words are plotted in Figures 5 and 6. Figure 5a shows the ERPs at a single scalp site (Cz) contrasting repeated and unrelated targets (the REPETITION effect), and Figure 5b shows the same data but contrasting all high- and low-frequency words (the FREQUENCY effect). Plotted in Figure 6 are the data from 15 scalp sites used in the data analyses. This figure shows the REPETITION effect separately for low-frequency and high-frequency words.

N250: 150–275 ms target epoch. While there were no main effects of REPETITION or FREQUENCY, there was a robust REPETITION × FREQUENCY × ANT-POST interaction ($F(4,92) = 6.35$, $p = .0056$) indicating that the size of the priming effect for the low- and high-frequency words differed. To better understand this interaction, we followed up the omnibus ANOVA with separate analyses for high- and low-frequency items. For low-frequency words, there was a main effect of REPETITION
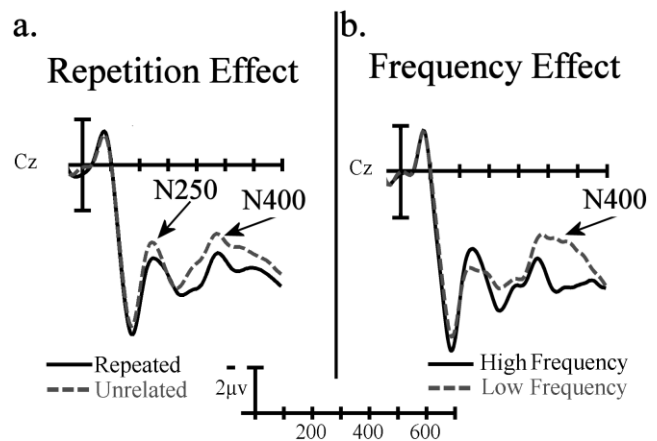

Figure 5. ERPs from the Cz scalp site time-locked to target onset for (a) repeated (solid) and unrelated (dashed) words (REPETITION effect); and (b) for high-frequency (solid) and low-frequency (dashed) words (FREQUENCY effect). In this and all subsequent ERP figures, negative voltages are plotted upward. Refer to Figure 4 for electrode locations. Note that while we have used arrows in this and subsequent figures to label the components of interest, due to the close temporal overlap of prime, mask, and target stimuli in the masked priming paradigm, it is unlikely that the true morphology of the underlying ERP effects of interest conform to the physical peaks noted here.

($F(1,23) = 5.97$, $p = .023$) as well as a significant interaction of REPETITION × ANT-POST ($F(4,92) = 3.52$, $p = .05$)—the repetition effect was larger over anterior electrodes (see Figure 6) compared to posterior sites. For high-frequency words, there was no main effect of REPETITION and only a marginal REPETITION × ANT-POST interaction ($F(4,92) = 2.82$, $p = .069$), and here it was the repeated targets that produced more negative ERPs at anterior sites (i.e., the opposite pattern as for low-frequency words).

N400: 375–500 ms target epoch. As can be seen in Figures 5 and 6, repetition effects are clearly visible in this epoch especially over more posterior sites (interaction of REPETITION × ANT-POST [$F(4,92) = 11.91$, $p = .0001$]). But importantly, there was again an interaction between the FREQUENCY and REPETITION factors ($F(1,23) = 4.47$, $p = .046$). We followed up with separate ANOVAs for the high- and low-frequency words. For the high-frequency words, there were both main effects of REPETITION ($F(1,23) = 7.64$, $p = .011$) as well as an interaction between REPETITION and ANT-POST ($F(4,92) = 6.9$, $p = .003$) indicating that unrelated high-frequency target words produced a more negative-going response than repeated high-frequency target words especially over more posterior sites (at the parietal sites there was a −1.3 µV difference and at frontal sites a −.65 µV difference—see Figure 6). For low-frequency words, there was also an interaction between REPETITION and ANT-POST ($F(4,92) = 5.04$, $p = .02$); however, this interaction appears to result more from a small reversal of priming effects from the front to the back of the head. At anterior sites, repeated low-frequency target words were actually more negative-going than unrelated low-frequency targets resulting in a positive difference (+1.0 µV) while at parietal sites there was a small negative difference (−.24 µV) reflecting the fact that unrelated low-frequency words were slightly more negative-going than repeated low-frequency words (see Figure 6, right panel). One observation that is clear from examining the right side of Figure 6
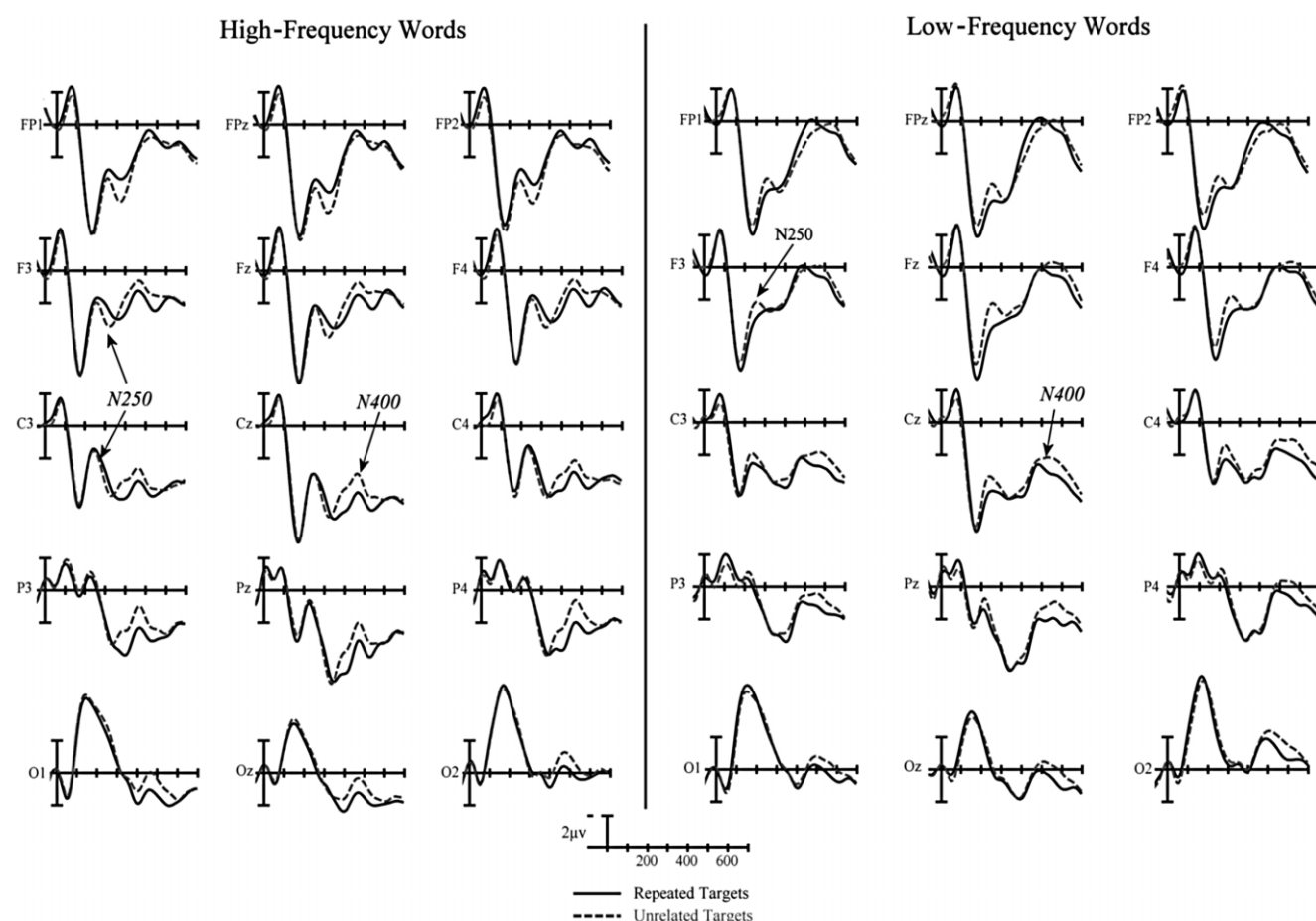
Figure 6. ERPs from 15 scalp sites for repeated (solid) and unrelated (dashed) targets for high-frequency words (left panel) and low-frequency words (right panel).

is that a substantial portion of what appears to be N400 activity occurs after the traditional 500 ms cut-off for the measurement of the N400.

Time-course analysis. To better characterize the temporal profile of the above effects, we also performed two sets of time-course analyses on the ERP data in six consecutive latency bins starting at 100 ms posttarget onset and going until 700 ms for both low-frequency and high-frequency words. The results of these analyses are reported in Figure 7 along with topographic maps of the priming effect in each epoch.

Discussion

The results of Experiment 1 show the predicted pattern of effects in the N400 ERP component, with high-frequency words generating stronger repetition priming effects than low-frequency words. Furthermore, the time-course analysis (Figure 7) clearly shows that these effects are not only stronger for high-frequency words, but they also peak earlier. Whereas the bulk of the N400 repetition effect for high-frequency words can be seen in the 400–500 ms time window, the effect is maximal in the 500–600 ms time window for low-frequency words. This pattern of priming effects seen on the N400 component is therefore perfectly in line with the predicted time-course of lexically driven repetition priming effects presented in the introduction (see Figure 2).

Concerning priming effects on the N250 component, however, we found an unexpected interaction in the opposite direction in this time window. Here, repetition priming effects were present for low-frequency words, with repeated targets generating less negative-going waveforms than unrelated targets in anterior electrode sites (i.e., the standard N250 repetition priming effect—see Holcomb & Grainger, 2006). High-frequency words, on the other hand, showed a bipolar effect with a small reversal of the standard N250 repetition priming effect in anterior sites. Given that the N250 component is thought to mostly reflect sublexical processing (e.g., Grainger & Holcomb, 2009; Holcomb & Grainger, 2006), we expected to see repetition priming effects that were unaffected by word frequency.

One possible explanation for the pattern of priming effects seen for high-frequency words in the N250 component is that these prime words were processed so efficiently that meaning representations were rapidly activated enabling the resetting of activation at the level of form representations. Indeed, in prior work (Holcomb & Grainger, 2007), we reported that the N250 repetition priming effect diminished with an increase in stimulus onset asynchrony (SOA). In Experiment 1 of the Holcomb and Grainger (2007) study, prime words were presented for 40 ms followed by a backward mask of varying duration. The stimuli were 5-letter English words with an average frequency of 27 per million (range 0–933). With a 60 ms SOA (i.e., 20 ms backward mask), there was a strong N250 repetition priming effect that was found to be greatly attenu-
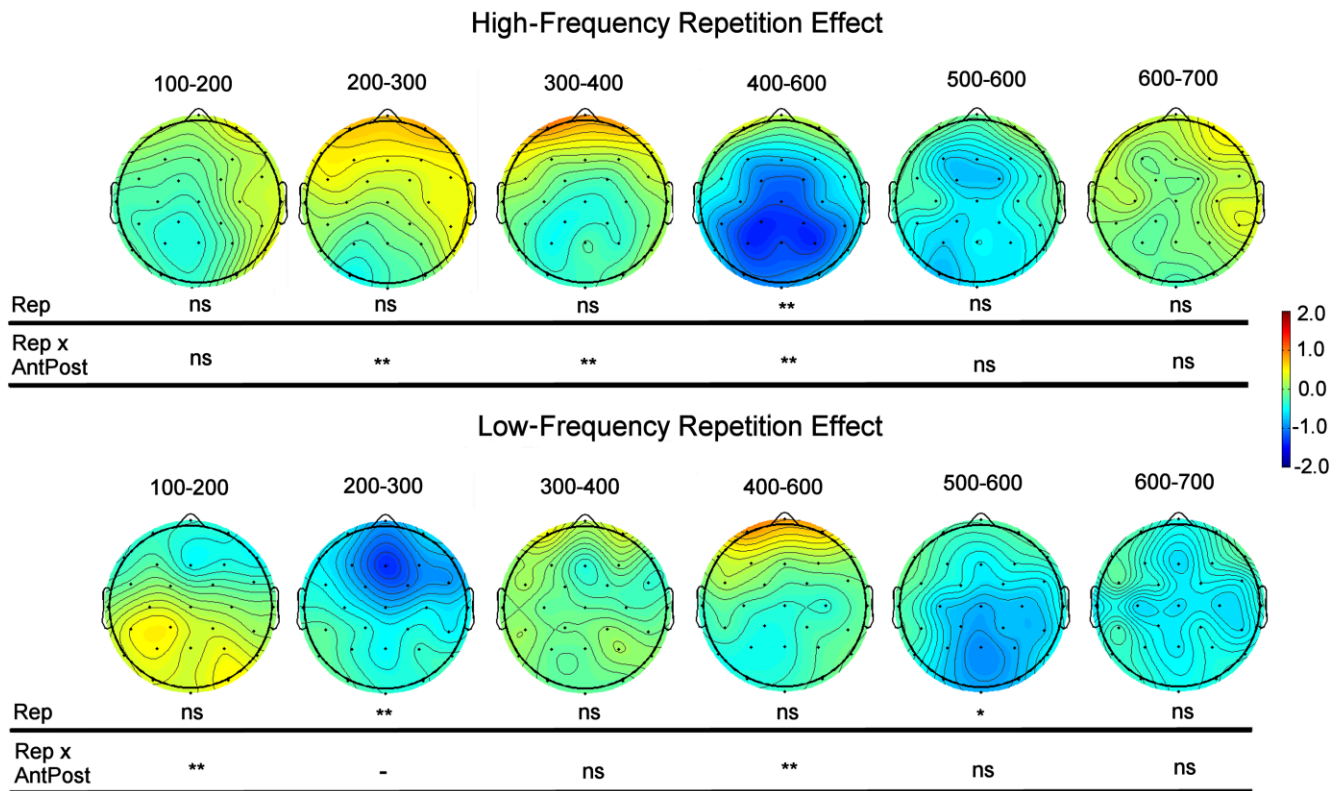
High-Frequency Repetition Effect

Rep	ns	ns	ns	**	ns	ns
Rep x AntPost	ns	**	**	**	ns	ns

Low-Frequency Repetition Effect

Rep	ns	**	ns	ns	*	ns
Rep x AntPost	**	–	ns	**	ns	ns

Figure 7. Time-course analyses of the REPETITION (unrelated–repeated) effect for consecutive 100 ms bins for high- (top) and low- (bottom) frequency target words (ns = $p > .1$; – = $p < .1 > .05$; * = $p < .05 > .01$; ** = $p < .01$).

ated by an increase in SOA, and completely disappearing at the 300 ms SOA.[3] At the same time, the N400 repetition priming effect was largely unaffected by the SOA manipulation. Holcomb and Grainger (2007) argued that with longer SOAs, prime stimuli are gradually processed as separated perceptual events (i.e., with less and less integration of form-level information across primes and targets). This encourages the triggering of reset mechanisms in order to reduce interference from prime-related activity during target processing (Grainger & Jacobs, 1999). These reset mechanisms only affect form-level processing, hence the selective influence of SOA on the N250 component and not the N400 component.

It is therefore possible that for the high-frequency words tested in the present study, the 70 ms SOA used in Experiment 1 was sufficiently long to trigger reset mechanisms and reduce priming effects on the N250. If this is indeed the case, then by shortening the prime-target SOA in Experiment 2, we should now observe repetition priming effects for high-frequency words in the N250 time window. These priming effects on the N250 component should be similar in magnitude to those seen with low-frequency words, while priming effects on the N400 should be larger for high-frequency words. This is because the predicted greater effects

of ERP repetition priming should start to emerge only when processing begins to involve lexical representations.

Experiment 2

Given the above explanation of the pattern of N250 repetition priming effects seen to high-frequency words in Experiment 1, in Experiment 2 we reduced the prime-target SOA to 50 ms in order to reduce the possibility of reset mechanisms affecting processing of high-frequency prime stimuli. This was done by simply removing the backward mask from the procedure used in Experiment 1. We again predict that N250 repetition effects should be similar for low- and high-frequency words, and we also expect to replicate the greater and earlier peaking N400 repetition effect for high-frequency words compared with low-frequency words that was found in Experiment 1.

Methods

Participants. Twenty-four native English speaking Tufts University students (12 male, mean age 20 years) were recruited and received compensation for their participation. All were right-handed, and had normal or corrected-to-normal visual acuity with no history of neurological insult or language disability. All participants reported that they learned no other language before the age of five. None of these participants had taken part in Experiment 1.

Stimuli and procedure. Stimuli were the same as tested in Experiment 1. The procedure for stimulus presentation was iden-

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3. In the Holcomb and Grainger (2007) study, repetition priming effects were still evident on the N250 component at an intermediate SOA of 180 ms. The fact that there was no effect for high-frequency words with the 70 ms SOA of Experiment 1 in the present study can be simply attributed to the greater frequency of these words compared with the words tested in the Holcomb and Grainger study. As argued here, what determines the presence of an N250 repetition priming effect is a combination of SOA and prime word frequency.
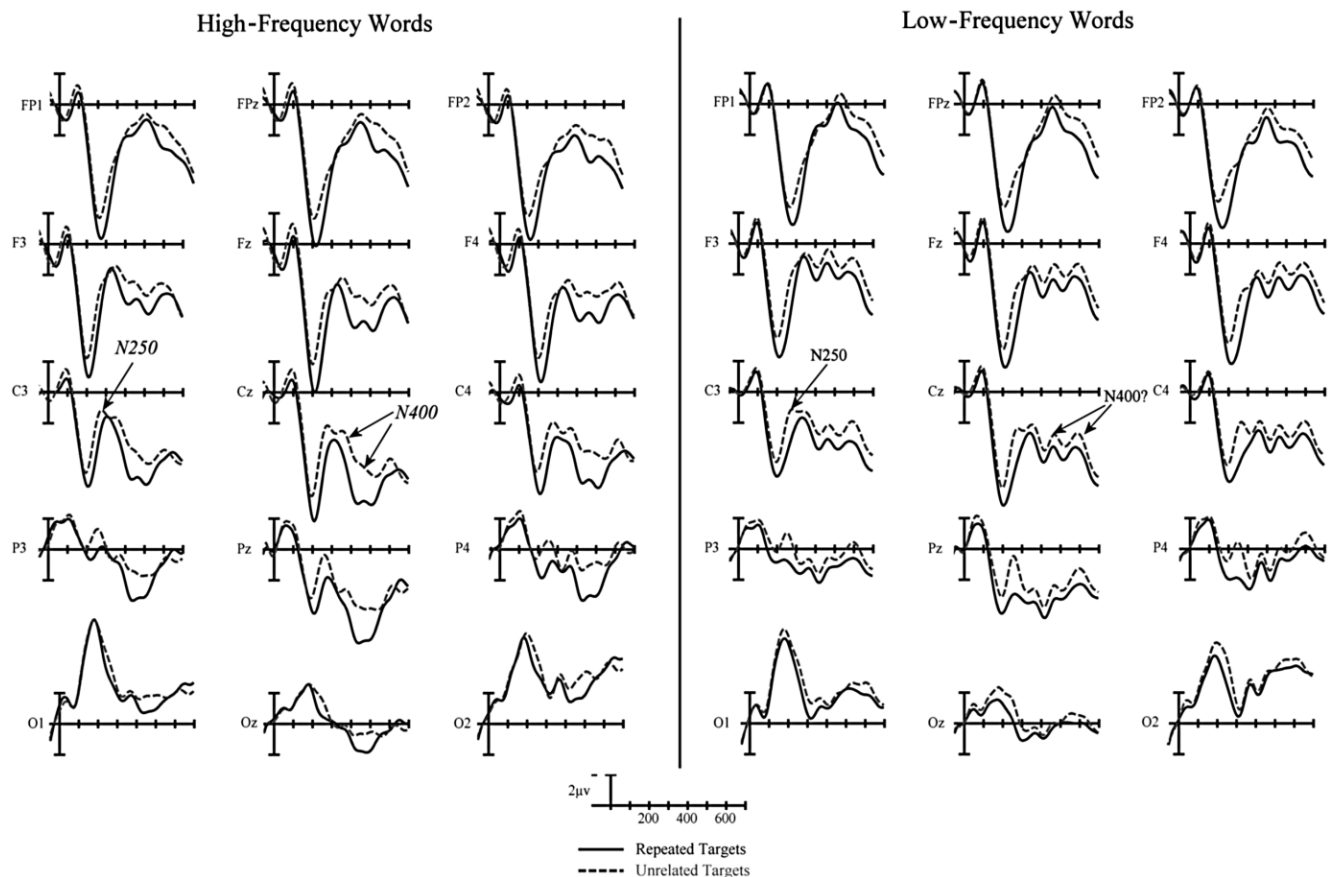
Figure 8. ERPs time-locked to target onset in the repeated (solid) and unrelated (dashed) conditions for the high-frequency (left panel) and low-frequency (right panel) words.

tical to that of Experiment 1 with the exception of the removal of the 20 ms backward mask, which therefore shortened the SOA from 70 ms to 50 ms. Note that this type of masked priming procedure, without a backward mask, is frequently and effectively used in behavioral masked priming studies.

EEG recording procedure. The EEG recording procedure of Experiment 1 was the same in Experiment 2.

Data analysis. The data in Experiment 2 was analyzed in the same way as the data in Experiment 1.

Results

Behavioral results. Participants detected an average of 86.5% of the animal probe words in the target position ($d' = 3.16$) and 3.3% in the prime position ($d' = .22$).

Event-related potentials. Grand-average ERPs from high-frequency repeated and unrelated trials are plotted alongside ERPs from low-frequency repeated and unrelated trials in Figure 8.

N250: 150–275 ms target epoch. Priming effects are visible in this epoch as seen in Figure 8. Both low-frequency and high-frequency unrelated targets show a more negative-going wave compared to repeated targets, resulting in a significant main effect of

REPETITION ($F(1,23) = 45.18$, $p = .0001$) and a REPETITION × ANT-POST interaction ($F(4,92) = 5.40$, $p = .006$). The latter effect is consistent with previous reports of a widespread but somewhat anterior distribution for the N250 effect (e.g., Holcomb & Grainger, 2006). Importantly, there were no interactions between frequency and repetition (all ps > .35) indicating that there were priming effects for both low- and high-frequency target words (see time-course analysis below).

N400: 375–500 ms target epoch. In this epoch, there was a main effect of FREQUENCY ($F(1,23) = 8.25$, $p = .009$), with low-frequency words producing more negative-going ERPs than high-frequency words. There was also a main effect of REPETITION ($F(1,23) = 11.24$, $p = .003$), with unrelated targets showing greater negativity than repeated targets (see Figure 8). In addition, there were interactions between REPETITION and ANT-POST ($F(4,92) = 4.90$, $p = .01$) and between FREQUENCY, REPETITION, and ANT-POST ($F(4,92) = 2.56$, $p = .044$). As can be seen in Figure 8a and 8b, it appears as though the repetition effects for high-frequency words are greater than those for low-frequency words, especially towards the back of the head. Follow-up analyses indicated that for high-frequency words there was a large effect of REPETITION (main effect: $F(1,23) = 12.33$, $p = .002$) and an interaction of REPETITION with ANT-POST ($F(4,92) = 10.33$, $p = .0001$), but for low-frequency words there were no significant main effects or interaction involving REPETITION (all ps > .17) in this epoch.

High-Frequency Repetition Effect

	100–200	200–300	300–400	400–600	500–600	600–700	
Rep	ns	**	ns	**	**	ns	
Rep x AntPost	ns	**	**	**	ns	**	

Low-Frequency Repetition Effect

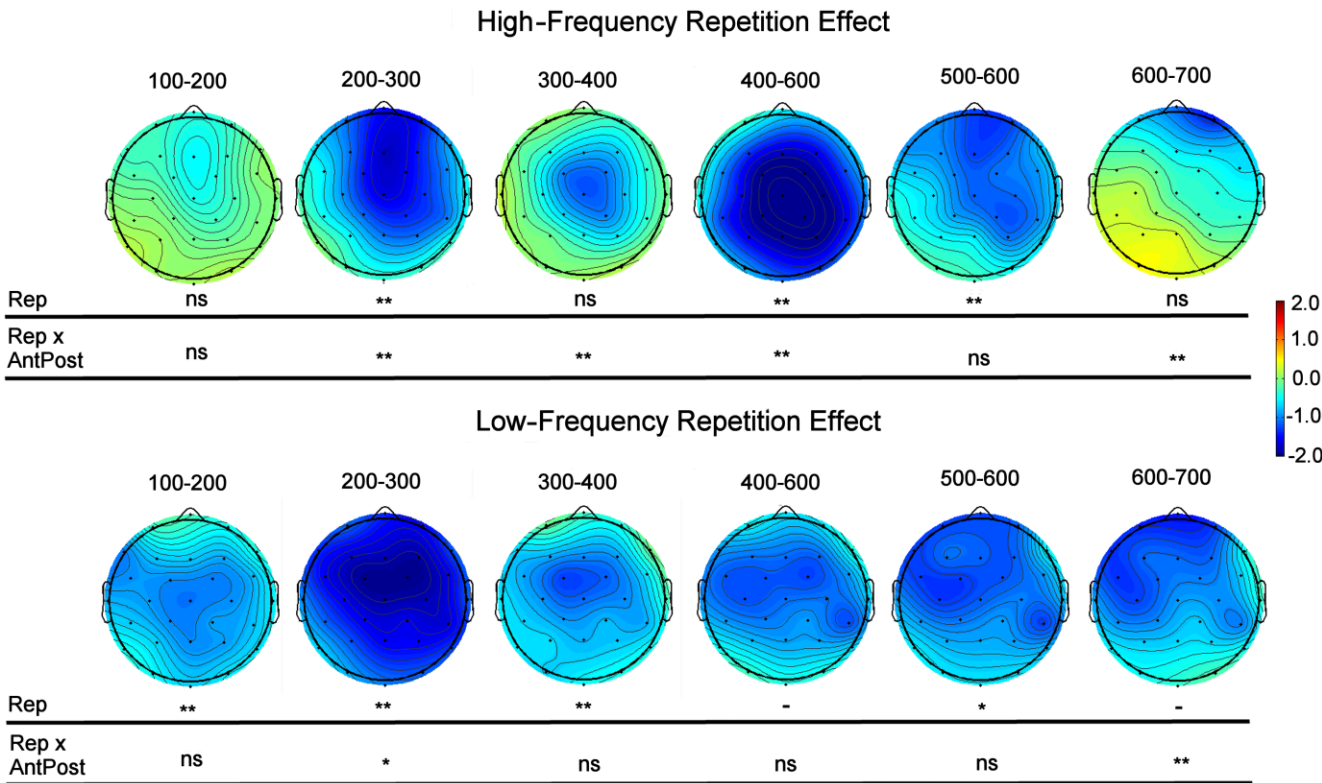|	100–200	200–300	300–400	400–600	500–600	600–700
Rep	**	**	**	–	*	–
Rep x AntPost	ns	*	ns	ns	ns	**

Figure 9. Time-course analyses of the REPETITION (unrelated-repeated) effect for consecutive 100 ms bins for high- (top) and low- (bottom) frequency target words (ns = $p > .1$; – = $p < .1 > .05$; * = $p < .05 > .01$; ** = $p < .01$).

Time-course analysis. As in Experiment 1, to better characterize the temporal profile of the above effects, we also performed two sets of time-course analyses on the ERP data in six consecutive latency bins starting at 100 ms posttarget onset and going until 700 ms for both low- and high-frequency words. The results of these analyses are reported in Figure 9. As can be seen from the voltage maps, high-frequency words produced an early unrelated more negative than repeated word response that had widespread but somewhat more anterior distribution between 200 and 300 ms, and then a larger and more posteriorly distributed unrelated more negative than repeated response between 400 and 500 ms. Low-frequency words generated a similar response between 200 and 300 ms, but did not show the clear later response; instead these items tended to show what appears to be a smaller and more prolonged (going all the way to 700 ms) negativity to unrelated compared to repeated words.

Discussion

By reducing the prime-target SOA in Experiment 2, we were able to reinstate repetition priming effects for high-frequency words in the N250 component. By reducing the SOA, we expected to promote prime-target integration processes and prevent potential reset mechanisms from eliminating prime-related activity at the level of form representations. The results of Experiment 2 suggest that we were successful in this respect. Experiment 2 also provided a replication of the interactive effects of word frequency and masked repetition priming found on the N400 component in Experiment 1. Once again, the N400 repetition effect in the traditional N400 window (350–500 ms) was greater for high- than low-

frequency words. Moreover, when an N400 effect emerged for low-frequency words, it did so during a later measurement window (500–600 ms).

General Discussion

Two experiments measured ERP repetition priming effects for low-frequency and high-frequency words in a masked priming paradigm. In Experiment 1, primes were presented for 50 ms and followed by a backward mask for 20 ms prior to presentation of the target immediately after the backward mask. In Experiment 2, the 20 ms backward mask was removed. In both experiments, participants had to respond by pressing a response key whenever they saw an animal name. Animal names appeared randomly as targets on 30% of trials, and as prime stimuli on 7% of trials. ERPs were analyzed for all critical trials where stimuli were not animal names. The results can be summarized as follows. In Experiment 1, ERP repetition effects were found for low-frequency words but not for high-frequency words in the N250 ERP component, while N400 ERP repetition effects were larger and peaked earlier for high-frequency words than low-frequency words. In Experiment 2, ERP repetition effects were found for both low-frequency and high-frequency words in the N250 component, and once again N400 ERP repetition effects were greater and peaked earlier for high-frequency than for low-frequency words.

N400 Repetition Effect

Perhaps the key finding of the present study is the interaction between word frequency and repetition priming seen in the N400

component in both experiments. Repetition primes generated less negative-going waveforms than unrelated primes, and this priming effect was greater (larger amplitude differences) and peaked earlier for high-frequency words than for low-frequency words. This interaction between the effects of word frequency and masked repetition priming therefore differs from what has been reported in behavioral studies using the lexical decision task. In these studies, masked repetition priming effects have been found to be statistically equivalent for high-frequency and low-frequency words (i.e., additive effects of Frequency and Repetition), or in certain conditions greater for low-frequency words than high-frequency words (see Kinoshita, 2006, for a review).

In the introduction, we offered one explanation for why this pattern of effects might be expected in behavioral measures of masked repetition priming. We showed that a simple linear accumulator model of lexical activation, combined with response read-out triggered when a criterion level of activation is attained, could generate additive or interactive effects of Frequency and Repetition priming. Lexical activation rises faster for high-frequency words than low-frequency words, such that the former reach the criterion level for response read-out earlier than the latter. Repetition primes provide an initial activation advantage upon target word presentation compared with unrelated primes, and therefore target-driven activation reaches the criterion level earlier following a repetition prime than an unrelated prime. What critically determines the nature of the Frequency × Repetition interaction is the difference in the initial advantage in prime-generated lexical activation for high-frequency words over low-frequency words in the repetition prime condition (see Figure 1).

It was further predicted that one might expect to observe exactly the opposite interaction effect when using ERP measures of target processing, when these measures reflect the build-up of activation in lexical (and therefore frequency-sensitive) representations. This prediction was made by examining changes in the activation values in the repetition prime and unrelated prime conditions over time, when these changes are simulated with a sigmoid activation function (see Figure 2). Priming was simulated by having activation accumulation start earlier in the repetition condition than in the unrelated condition. This led us to predict that lexically driven priming effects should be greater (bigger amplitude differences) and peak earlier for high-frequency words than low-frequency words. It was this key prediction that was put to the test in the present study, and the results revealed the predicted pattern of priming effects on the N400 ERP component.

In our general account of visual word recognition, word frequency effects are hypothesized to arise as soon as contact is made with whole-word representations. More precisely, it is differences in connection strengths between sublexical representations and whole-word representations, and between whole-word representations and semantic representations that are thought to be the basis of word frequency effects. As argued before, it is these differences in connection strengths that enable a faster build-up in activation for high-frequency words compared with low-frequency words. Therefore, during target word processing, frequency effects ought to become visible in the ERP signal starting around 300 ms posttarget onset (at the end of the N250 component), which is when sublexical representations are thought to make contact with whole-word representations according to our time-course model that maps ERP effects obtained in the masked priming paradigm with component processes in visual word recognition (Holcomb & Grainger, 2006; 2007; see Grainger & Holcomb, 2009, for a review). If one plots the difference waves for the repetition priming effect in the
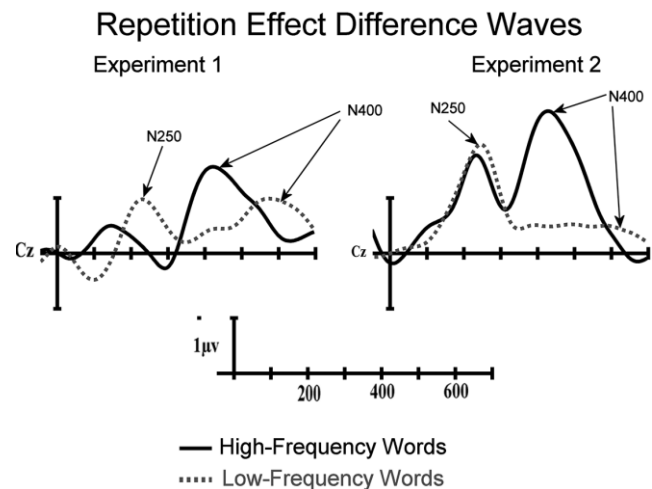

Figure 10. Difference waves calculated by subtracting Repeated from Unrelated target ERPs at the Cz electrode site. High-frequency (solid) and low-frequency (dashed) words are overplotted from Experiment 1 (left) and 2 (right).

high-frequency and low-frequency conditions (see Figure 10 for electrode site Cz), then starting around 300 ms posttarget onset one obtains a pattern of effects that is quite similar to the pattern predicted by our sigmoid accumulator model.

Furthermore, the present study provides another example of how ERP effects can dissociate from those seen in behavioral measures. There are many other examples of such dissociations, and all provide important additional constraints with respect to the mechanisms hypothesized to be underlying the effects under study. For example, Holcomb, Grainger, and O'Rourke (2002) found that although lexical decision response times were faster to words with many orthographic neighbors compared with few orthographic neighbors, N400 amplitude was found to be greater to the high neighborhood density words. This was taken as support for the hypothesis that lexical decision responses can be triggered on the basis of information that is specifically recruited for performing that task, such as global lexical activation (Grainger & Jacobs, 1996). In a masked priming study of language production, Blackford, Holcomb, Grainger, and Kuperberg (submitted) found a dissociation between the effects of semantically related prime words on picture-naming latencies, and the same effects seen in modulations of N400 amplitude. Semantically related prime words interfered with picture naming compared with unrelated primes, yet N400 amplitude was found to be reduced in the semantically related condition (see Dell'Acqua et al., 2010, for the same pattern in a picture-word interference paradigm). This was taken as evidence that the semantic interference effect seen in picture-naming latencies was being driven by processes occurring after lexical access (recovery of the phonological form that corresponds to the picture name). Such dissociations provide a perfect illustration of how ERP recordings can be used in combination with behavioral measures in order to provide strong constraints on possible interpretations of a given phenomenon.

N250 Repetition Effect

According to the above account of repetition priming effects, we expected to observe repetition priming effects of about the same size to low-frequency and high-frequency words in the N250 ERP

component. This is because the bulk of activity in the N250 component is thought to reflect sublexical processing, with lexical influences appearing towards the end of this time window. Such sublexical processing is assumed to be less affected by word frequency compared with processing that is centered on whole-word representations.

Although the predicted pattern of priming effects in the N250 time window was observed in Experiment 2, a different pattern was seen in Experiment 1, where there was little evidence for a repetition effect for high-frequency words, and at the same time a strong repetition effect for low-frequency words. Our explanation for the pattern seen in Experiment 1 is that the 70 ms SOA used in that experiment was sufficiently long for high-frequency prime words to be processed as a distinct perceptual event from the following target words.[4] This is thought to block prime-target integration processes and trigger reset mechanisms that are used to rapidly suppress activity in all representations that can potentially interfere with processing of upcoming stimuli (Grainger & Jacobs, 1999; Humphreys, Besner, & Quinlan, 1988). Semantic representations are not affected by such reset mechanisms, since multiple semantic representations must remain simultaneously active in order to enable sentence-level integration (Holcomb & Grainger, 2007). This therefore explains why there was no repetition effect for high-frequency words in the N250 component, and a robust effect for the same words in the N400 component in Experiment 1. It is

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4. It should be noted that prime probe detection rate dropped from 11% in Experiment 1 to 3% in Experiment 2.

the slower processing of low-frequency words that prevents them from being processed as a separate perceptual event, thus maintaining prime-target integration with these stimuli; hence, the presence of an N250 repetition effect for low-frequency words in Experiment 1. Thus, the results of the present study again provide evidence that the N250 ERP component revealed in masked priming studies (e.g., Holcomb & Grainger, 2006; see Grainger & Holcomb, 2009, for a review) reflects the bulk of activity building up in sublexical form representations.

Conclusions

Two masked priming experiments investigated the influence of word frequency on repetition priming effects over the complete time-course of target word recognition by measuring ERPs. With an SOA small enough to prevent high-frequency primes from being processed as being perceptually distinct from targets (i.e., the 50 ms SOA of Experiment 2), we found comparable repetition effects for low-frequency and high-frequency words on the N250 ERP component. This was expected given our interpretation of the N250 component as mostly reflecting activity in sublexical representations. On the other hand, masked repetition priming effects were found to be greater in magnitude and to peak earlier for high-frequency words than low-frequency words during the time window of the N400 component. This pattern of N400 priming effects was predicted by a frequency-sensitive accumulator model using a sigmoid activation function, with accumulation of lexical activity starting earlier in the repetition prime condition.

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