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The Low-Frequency Encoding Disadvantage: Word Frequency Affects Processing Demands

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Abstract

Low-frequency words produce more hits and fewer false alarms than high-frequency words in a recognition task. The low-frequency hit rate advantage has sometimes been attributed to processes that operate during the recognition test (e.g., L. M. Reder et al., 2000). When tasks other than recognition, such as recall, cued recall, or associative recognition, are used, the effects seem to contradict a low-frequency advantage in memory. Four experiments are presented to support the claim that in addition to the advantage of low-frequency words at retrieval, there is a low-frequency disadvantage during encoding. That is, low-frequency words require more processing resources to be encoded episodically than high-frequency words. Under encoding conditions in which processing resources are limited, low-frequency words show a larger decrement in recognition than high-frequency words. Also, studying items (pictures and words of varying frequencies) along with low-frequency words reduces performance for those stimuli.

Keywords

word frequency; memory; working memory; encoding

Success in memory is commonly attributed to the way information is encoded, stored, and retrieved. Past experience with the information also plays a role in whether it is remembered. The effect of prior experience with words (measured as word frequency) on ability to recognize those words in an episodic task has been extensively investigated (e.g., Glanzer & Adams, 1985; Guttentag & Carroll, 1997; Joordens & Hockley, 2000; MacLeod & Kampe, 1996; Reder et al., 2000). A mirror effect is typically found when word frequency is a factor such that hits are greater for low-frequency items but false alarms are greater for high-frequency items.

Word Frequency Effects

The finding that low-frequency words show an advantage in recognition, for both hits and false alarms, has been explained within a number of frameworks. Recent single process theories explain the mirror effect as the result of special characteristics of low-frequency words, such as having more unique representations (in terms of either letter features or semantic features) than high-frequency words, thus making them more likely to be recognized correctly and less likely to be spuriously recognized (McClelland & Chappell, 1998; Shiffrin & Steyvers, 1997). The source of activation confusion (SAC) model provides a dual-process account of the word frequency mirror effect (Reder et al., 2000). Joordens and Hockley posited a similar account (Joordens & Hockley, 2000). These accounts focus primarily on effects at retrieval.

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Dual-process theories of recognition assert that recognition tests allow the use of two processes: recollection, a retrieval of contextual information related to the encoding event, and familiarity, an assessment of memory strength (Jacoby, 1991; Joordens & Hockley, 2000; Mandler, 1980; Reder et al., 2000; Yonelinas, 1994). The remember–know paradigm is often used as an assessment of recollection and familiarity based responses (Tulving, 1985). In this paradigm, participants are asked to make a *remember* response when they recognize an item and can recall some detail about the context of having studied the item in the task. *Know* responses are made when the participant feels the item is familiar but is unable to recall any details about the context in which the item was studied. Remember responses are thought to index the recollection process, and know responses are thought to index the familiarity process.

The SAC model is a dual-process model of memory. *Source of activation confusion* indicates that people are unable to distinguish between activation due to recent exposure and activation due to a buildup of prior exposures. This principle is central to the SAC explanation of the word frequency mirror effect (see Reder et al., 2000). The strength of the word concept node is affected by whether the word has been recently seen and how often it has been seen previously. High-frequency words have higher conceptual strength due to prior exposure, and thus high-frequency lures are more likely to produce familiarity-based false alarms than low-frequency lures.

Another principle of SAC is that activation spreads along links between nodes according to the number and relative strength of the links. Therefore, less activation spreads along any one link from a node that has a greater number of links. A high-frequency word has more contextual associations than a low-frequency word and thus can be expected to have more contextual links emanating from its word concept node. This makes it less likely that a sufficient amount of activation will spread from a high-frequency word concept node to its bound episode node than from a low-frequency word concept node to its bound episode node. Recollection-based responses are made when the activation of an episode node surpasses threshold. Familiarity-based responses are made when recollection fails and activation of a word concept node surpasses threshold. Therefore, SAC predicts more hits to low-frequency words than to high-frequency words but also expects that this difference should be seen in the remember responses.

The SAC model of the word frequency mirror effect was formally implemented in Reder et al. (2000). The empirical results from that article showed that the hit portion of the mirror effect was driven by remember responses whereas the false alarm portion was due to know responses. The SAC model successfully fit the data. Similar to the Reder et al. finding, Gardiner and Java (1990) found that for the hit portion of the mirror effect, there were more remember responses to low-frequency targets than to high-frequency targets. SAC also predicts that there will be more know responses to high-frequency than to low-frequency words, but Gardiner and Java found no evidence of this. To confirm their findings of a difference in know responses, Reder et al. (2000) analyzed the results of five previous studies testing the word frequency mirror effect with remember–know judgments and found a significant difference between know responses to high-and low-frequency words, such that high-frequency words produced more know responses.

The SAC explanation for the standard mirror effect is based on the spreading of activation at retrieval and does not rely on encoding factors. Other explanations have focused more on the encoding aspect of memory to account for the mirror effect. For example, it has been proposed that part of the advantage for low-frequency words in recognition is due to low-frequency words being encoded more distinctively (Eysenck & Eysenck, 1980). This is somewhat reminiscent of the account provided by single-process models (McClelland & Chappell, 1998; Shiffrin & Steyvers, 1997), although those models propose that the encoding advantage is inherent to the words rather than invoked by the task.

One of the first theories developed to explain the mirror effect is the attention likelihood theory (ALT), which focuses on differences in processing at encoding for high- and low-frequency words. ALT (Glanzer & Adams, 1990; Glanzer, Adams, Iverson, & Kim, 1993) claims that some classes of stimuli receive more attention than others and thus have more features "marked" at study. When a test item is presented, likelihood ratios are calculated on the basis of the number of features marked, the proportion of marked features an old item of this type is expected to have, and the proportion of marked features a new item is expected to have. Low-frequency words are thought to receive more attention at study and have more features marked. At test, participants are assumed to be aware that low-frequency words are better remembered than high-frequency words. Thus, when likelihood ratios are calculated, more features are marked for old low-frequency words, providing for the hit rate portion of the mirror effect, and fewer features are expected to be marked for new high-frequency words, providing for the false alarm portion of the mirror effect.

There are several problems with ALT as it was originally proposed. ALT links the hit rate and false alarm rate portions of the mirror effect by ascribing both effects to the number of features marked and expected to be marked. Therefore, the theory predicts that manipulations that eliminate or reverse the hit portion of the mirror effect will also eliminate the false alarm portion. Hirshman and Arndt (1997) demonstrated in several experiments that the hit rate portion of the mirror effect is eliminated by various manipulations whereas the false alarm portion remains. Stretch and Wixted (1998) also provided evidence that a criterion shift is not involved in the word frequency mirror effect, as ALT claims. They strengthened high-frequency words at study, which a criterion shift model predicts should increase the number of features expected to be marked for high-frequency words. This increase in the number of features expected to be marked should decrease the proportion of false alarms to high-frequency words; however, Stretch and Wixted found that high-frequency words continue to produce more false alarms than low-frequency words. Neither of these criticisms of the ALT model disprove the general theoretical principle on which the model is based: that low-frequency words receive more attention at encoding.

Having discussed the effects of word frequency on recognition extensively, we should note that not all tasks show an advantage for low-frequency words. Word-naming tasks show that high-frequency words are responded to faster than low-frequency words (e.g., Frost & Katz, 1989). High-frequency words show an advantage when memory is tested with recall tasks (Deese, 1960), although only when high- and low-frequency words are studied on separate lists (MacLeod & Kampe, 1996; Watkins, LeCompte, & Kim, 2000). Associative recognition tasks also show a high-frequency advantage (Clark, 1992). Even in recognition, the low-frequency advantage is affected by list composition. There is some evidence that high-frequency words show an advantage when items are presented on pure lists (Dewhurst, Hitch, & Barry, 1998) and that when the proportion of high-frequency words on a list is increased, the low-frequency advantage increases (Malmberg & Murnane, 2002). Also, medium-frequency words presented on a list with high-frequency words produced more remember responses than medium-frequency words presented on a list with low-frequency words (McCabe & Balota, 2005)

Hypothesis and Prior Evidence

Findings from tasks other than recognition suggest that a high-frequency advantage is occurring in addition to the low-frequency advantage that occurs in recollection. Recall, associative recognition, word-naming, and varied list composition tasks must differ from a simple recognition task in a way that produces a high-frequency advantage. One possibility is that both the SAC interpretation of the mirror effect and the major premise of ALT are correct. That is, the word frequency mirror effect may be due to advantages for low-frequency words in recollection as suggested by SAC, but these advantages clearly require successful episodic encoding in order to operate. According to SAC, a low-frequency advantage in recollection cannot occur without a binding between the conceptual representation of the word and the episodic context of the word.

Perhaps the additional attention that may occur for low-frequency words is in fact necessary to create the binding between low-frequency words and their contexts. If it is true that low-frequency items are more difficult or cognitively taxing to encode than high-frequency items, then the mirror effect should occur only when sufficient resources are available to encode low-frequency words episodically. In order to produce evidence of a low-frequency encoding disadvantage using a recognition task, processing resources would need to be restricted at study. This would create a situation in which low-frequency words could not be effectively encoded and thus the low-frequency retrieval advantage could not operate.

Prior evidence has been found for the claim that low-frequency words require more processing resources at study. Rao and Proctor (1984) demonstrated that when encoding is self-paced, participants will study low-frequency words for longer periods of time than high-frequency words. However, this may indicate only that low-frequency words are preferentially encoded, rather than that this additional encoding is required in order to reveal a low-frequency advantage.

Kinoshita (1995) instructed participants to attend to stimuli other than the studied word, while words of different frequencies were presented. That is, words were presented in between two digits on a computer screen; in the attended condition participants were told to read the word aloud but ignore the digits, whereas in the unattended condition they were told to ignore the word and judge whether the parity of the two digits matched. A frequency effect was found in the attended condition for remember responses such that low-frequency words were better remembered. Although the unattended condition provides a test in which encoding of the words may have been limited, remember responses were at floor (less than 5% hits) and know responses were very low (7%−10% hits, approximately equal with know false alarms). These floor effects make it difficult to interpret whether the low-frequency advantage would still occur under reduced attention conditions. Experiment 2 attempted to remedy the floor effects, but remember hits (now at 7%−10%) were approximately equal to remember false alarms. This type of experiment provides a useful test of the low-frequency encoding disadvantage, but floor effects in the Kinoshita experiment make interpretation difficult.

The data from studies using cued-recall tasks following divided attention encoding conditions are more easily interpreted. In cued-recall tasks, high-frequency words are better remembered than low-frequency words. Although the inclusion of a secondary task during encoding reduced memory performance overall, it did not differentially reduce memory performance for high-frequency words (Naveh-Benjamin, Craik, Guez, & Dori, 1998; Naveh-Benjamin & Guez, 2000). The difference between high- and low-frequency performance remained approximately equal in the full-attention and dual-task-at-encoding conditions. However, when performance on the secondary task was analyzed, reaction times (Naveh-Benjamin et al., 1998) and overall accuracy (Naveh-Benjamin & Guez, 2000) were faster and more accurate during study of high-frequency words than study of low-frequency words. This supports the idea that low-frequency words draw more processing resources during encoding; however, the experiment did not demonstrate that a lack of processing resources for low-frequency words could reduce memory for those low-frequency words.

A recent imaging study also found that more attention is given to low-frequency words during encoding (de Zubicaray, McMahon, Eastburn, Finnigan, & Humphreys, 2005). Low-frequency words were associated with a larger blood oxygen level-dependent response in the left prefrontal cortex than were high-frequency words. The authors concluded that this finding supports the claim that low-frequency words receive more attention at study but does not rule out the possibility of additional effects due to word frequency occurring at test.

The idea that low-frequency words show an advantage in recognition due to increased attention at encoding alone (rather than an additional retrieval advantage) is contradicted to some degree by other studies of encoding time. No differences have been found in the word frequency effect between encoding times of 800 ms and longer (Hirshman & Palij, 1992). Thus, it seems that any low-frequency disadvantage at encoding is resolved prior to 800 ms of encoding time. This suggests, as Hirshman and Palij concluded, that if increased processing of low-frequency words occurs, it must occur during early stages of processing. Alternatively, they conclude that encoding factors might not play a role in the word frequency mirror effect. Malmberg and Nelson (2003) further tested this conclusion by shortening encoding times even further. In their Experiment 1, the low-frequency hit rate advantage did not occur for 0.25-s encoding but did occur for 2.5-s encoding. Their Experiment 2 found the hit rate advantage for both 1-s and 3-s encoding conditions but did not find a difference in the size of the effect at the two encoding times. The authors interpreted this result as indicating that there are two phases of study, an early phase in which low-frequency words are allocated more attention because they have uncommon structural aspects and a late phase in which attention is equal.

Miozzo and Caramazza (2003) investigated this early perceptual processing period using a picture/word-interference paradigm. They found that when participants were asked to name a series of pictures as quickly as possible, those pictures presented with low-frequency words had slower naming latencies than pictures presented with high-frequency words. This interference was reduced when participants read aloud the distractor words several times prior to their presentation in the picture-naming task. This study provides evidence that processing the perceptual characteristics of a low-frequency word may take more effort than accessing a high-frequency word, but it does not tell us whether interference would occur between these pictures and words in episodic recognition. It has not been shown that this increased effort in the perceptual processing stage would translate into reduced memory for either the picture or the word.

Prior studies that have examined working memory demands at encoding for words of differing frequency support the claim that low-frequency words use more attention. However, the need for additional processing time has been shown only with extremely short encoding times, and the need for additional processing capacity has been shown only in secondary task performance, rather than memory performance. No studies have demonstrated that recognition for low-frequency words is differentially affected by reducing processing resources at encoding. We argue that a minimum amount of attention must be paid to low-frequency words in order to encode them episodically and that this amount is greater than that required for high-frequency words. We also claim that the word frequency mirror effect is due to factors at retrieval but that sufficient episodic encoding of low-frequency words must occur to allow these retrieval factors to proceed. Four experiments are presented to test these claims.

Experiment 1

This experiment tested the idea that low-frequency items draw more attention during encoding than high-frequency items and that this attention can harm memory for simultaneously presented items. We measured the degree to which the study of a low-frequency word (as compared with the study of a high-frequency word) harms encoding of a secondary item. The design was inspired by Miozzo and Caramazza's (2003) word-naming study. The current study extended their finding by testing recognition memory for both the picture and the word following the study phase of the experiment. We also changed the procedure by asking participants to read the word aloud rather than name the picture. This was a more direct test of the idea that encoding of the word would affect ability to encode the picture. If low-frequency words demand more processing resources during encoding, then we would expect that memory for pictures presented with low-frequency words would be worse than memory for pictures presented with high-frequency words. We expect this encoding difference to affect binding, and thus the differences should be manifested in remember responses. Because participants were told to read the words aloud, this was their primary focus, and thus we hypothesized that their memory for the words would be minimally affected by the pictures. Therefore, we expected to see a typical word frequency mirror effect for word recognition.

Method

Participants—Twenty-four members of the Carnegie Mellon student body and community participated in this experiment for their choice of either partial course credit or payment. The average age of the participants was 23.7. All participants were native English speakers (defined as having learned English before age 5).

Materials—The pictures used in the task were photographs of 80 objects such as a pencil, a piano, a lemon, a refrigerator, balloons, and a mushroom. The simultaneously presented words were selected from the Medical Research Council database (Coltheart, 1981) available online at http://www.psy.uwa.edu.au/mrcdatabase/uwa_mrc.htm. The 40 high-frequency words had an average Kučera–Francis (Kučera & Francis, 1967) frequency of 146, ranging from 53 to 492. The 40 low-frequency words had an average Kučera–Francis frequency of 5, ranging from 1 to 10. Concreteness, imagability, and number of letters were held approximately constant, with average low- and high-frequency ratings, respectively, for concreteness at 558 and 554, imagability at 545 and 568, and number of letters being 6.3 and 6.0. The stimuli were presented using the PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993) on a Macintosh computer. A microphone and PsyScope button box were used to collect voice key responses.

Procedure—Participants were instructed that they would view pictures of objects with words superimposed on the pictures. They were asked to read the word aloud as quickly as possible but to try to pay attention to both the picture and the word. They were warned that they would be tested on their memory for both the picture and the word later in the experiment. Each participant wore a lapel microphone during the word-naming portion of the experiment, which began with six practice trials. Following the practice trials, participants viewed a series of 40 pictures, 20 presented with low-frequency words and 20 with high-frequency words, and read the words aloud. The 40 pictures and words were randomly selected for each participant from the pool of 80. The remaining 40 pictures and words were used as lures in the tests. Each participant viewed a different, randomly selected combination of words and pictures. Each trial began with a 500-ms fixation in the center of the screen. The microphone detected the onset of the voice response when the word was read aloud and immediately removed the stimulus from the screen. Following each response there was a 1-s pause before the next trial began.

Upon completion of the word-naming part of the experiment, the participants played a simple video game for 5 min. After the delay, participants were given the remember–know instructions (Gardiner, 1988). We referred to the *know* response as a *familiar* response because we think it is a more intuitive term. After participants read the instructions from the screen, the experimenter reviewed them orally and then asked the participant to summarize in his or her own words what each response indicated. Participants were also asked to respond as quickly and accurately as possible.

The picture test was always conducted first. Participants viewed the 40 old pictures and 40 new pictures and were asked to make remember–familiar judgments. Each picture was presented on the screen until the participant made a response. Following the picture test, participants viewed the 40 old words with 40 new words. Once again, the word remained on the screen until the participant made a response. Half of the words were high frequency and half low frequency.

Results and Discussion

The reaction times for the study phase of the experiment indicate how long each picture–word combination was available to be studied. We compared the reaction times for word naming of high-frequency words (M = 607 ms) and low-frequency words (M = 630 ms) using a paired-samples t test. The reaction times were not significantly different, $t(23) = -1.51$, $p = .14$. This indicates that study time was approximately equal for both types of stimuli, although the nonsignificant difference occurred in the direction of more study time for low-frequency words and pictures presented with them. It is important to note that following word naming there was a 1,500-ms delay before the next trial, which meant that participants may have been thinking about each stimulus pair for longer than the approximately 600 ms that it was presented on the screen.

We hypothesized that pictures presented with high-frequency words would be better remembered than those presented with low-frequency words, particularly in terms of remember responses. Figure 1 shows the remember and familiar hit rates as a function of word frequency. Paired-samples t tests showed significant effects of frequency for both remember hits, $t(23) = 4.32$, $p < .001$, and familiar hits, $t(23) = -2.20$, $p < .05$. The results of the picture recognition test show that memory was more accurate overall for pictures presented with high-frequency words than pictures presented with low-frequency words (low-frequency hits, $M = .73$; high-frequency hits, $M = .79$), $t(23) = 2.25$, $p < .05$. The advantage for pictures presented with high-frequency words was manifested in remember responses. Pictures presented with low-frequency words showed slightly more familiar responses. This was likely due to the dependence between remember and familiar responses, such that fewer remember responses will allow for more familiar responses to be made.

We also analyzed performance on the word recognition test with regard to hits and false alarms. Figure 2 shows hits and false alarms aggregated across remember and familiar responses. The typical mirror pattern of more hits and fewer false alarms to low-frequency words was found. Paired-samples t tests showed significant effects of frequency on both hits, $t(23) = -4.10$, $p < .001$, and false alarms, $t(23) = 4.12$, $p < .011$.

Remember and familiar hits were analyzed to determine whether the same patterns were found as in previous research (e.g., Reder et al., 2000). The SAC account of the word frequency mirror effect expects that the hit rate portion of the mirror effect will be driven by remember responses whereas the false alarm portion will be driven by familiar responses. Paired-samples t tests revealed that although the word frequency effect was significant for remember hits, $t(23) = -2.72$, $p < .05$, the difference was not significant for familiar hits, $t(23) = -0.972$, $p = .34$. We also found the expected effect for false alarms, such that remember false alarms (low frequency, M = 3%; high frequency, M = 6%) did not show a significant difference due to frequency, $t(23) = 1.87$, $p = .07$, whereas familiar false alarms (low frequency, M = 8%, high frequency, M = 17%) were significantly greater for high-frequency words than for low-frequency words, $t(23) = 3.49$, $p < .01$.

The results of Experiment 1 are consistent with the hypothesis that low-frequency words require more processing resources to be encoded than high-frequency words. The pairing of a low-frequency word with a picture led to worse memory for the picture than the pairing of a high-frequency word. This occurred despite the fact that the pictures shown with low-frequency words were present on the screen for slightly longer (although not significantly longer) than those presented with high-frequency words. This picture advantage with high-frequency words may be due to the low-frequency word using more working memory capacity during encoding than the high-frequency word and thus preventing the associated picture from being processed as effectively. It is interesting to note that the typical word frequency mirror effect occurred and that the pattern of remember and familiar responses was consistent with the SAC account of the word frequency effect. This supports the claim that processing of the low-frequency word occurred at the expense of processing of the picture. The low-frequency word was encoded at a sufficient level to allow the advantage for recollection at retrieval to occur.

Experiment 2

The results of Experiment 1 suggest that low-frequency words demand more processing capacity during encoding than high-frequency words. The second part of our hypothesis concerning a low-frequency encoding disadvantage states that this extra processing for low-frequency words is necessary for them to be episodically encoded (meaning bound to an experimental context). High-frequency words can be episodically encoded with comparatively little effort or working memory resources. Thus, we would predict that reducing available working memory capacity during encoding should harm recollection-based responses to low-frequency words to a larger extent than recollection-based responses to high-frequency words are harmed.

The most direct way to manipulate available processing capacity during encoding is to use a dual-task procedure. Previous experiments have manipulated participants' attentional demands while studying words of varying frequencies, but those experiments either suffered from floor effects (Kinoshita, 1995) or affected only the secondary task (Naveh-Benjamin et al., 1998; Naveh-Benjamin & Guez, 2000). The current experiment was designed to manipulate word frequency while dividing attention but maintaining a minimum level of memory performance. We instructed participants to give their best effort on the secondary task, rather than modulating their performance on that task to improve the memory task.

Method

Participants—The study included 32 participants from the Carnegie Mellon community with an average age of 20; participants received a choice of either course credit or payment for their participation. Three participants were dropped from the analysis for failing to follow instructions by not responding properly during the memory task. A fourth participant was dropped for having a negative average d'. Thus, the total number of participants in the study was 28. All participants were native English speakers.

Materials—A new set of 285 words were selected from the MRC database (Coltheart, 1981). Of those, the 120 high-frequency words had an average Kučera–Francis (Kučera & Francis, 1967) frequency of 178, ranging from 70 to 613. The 120 low-frequency words had a Kučera–Francis frequency of either 1 or 2, with the average being 1.5. Concreteness, imagability, and number of letters were held approximately constant, with average low- and high-frequency ratings, respectively, for concreteness at 402 and 398, imagability at 422 and 424, and number of letters being 6.1 for both groups. The remaining 45 words were medium-frequency (average Kučera–Francis frequency of 35, ranging from 25 to 50) and used as buffer items that were not tested. For the secondary task, voice files of the experimenter reading aloud the digits 1 through 9 individually were created. The stimuli were presented using the PsyScope software (Cohen et al., 1993) on two different Macintosh computers, one for the study list and one for the secondary task. A microphone and PsyScope button box were used to record voice key responses.

Procedure—At the beginning of the experimental session, all participants were given the same remember–familiar instructions as used in Experiment 1. They were then told that they would be studying two lists of words for later memory tests and that while studying one of the lists they would have to perform a secondary task. Following these instructions, half of the participants received the dual-task list and half received the single-task list. For the dual-task list, participants were told that they would be asked to do a serial addition task in which single digits would be read aloud from the computer and they would need to mentally add each digit to the previous digit heard and report the sum aloud. Note that this was more challenging than requiring them to calculate a running sum. One digit was heard every 4 s, and the list of digits was randomized for each participant. This task was modeled after the most effective task used in Hicks and Marsh's study of the effects of dual task on retrieval (Hicks & Marsh, 2000). The participants wore a microphone to record their responses in the secondary task. Each participant practiced the secondary task before studying any words by performing 15 trials in the serial addition task alone. Following the practice trials, participants were instructed to silently read the study words while performing the serial addition task. They were told to try to perform to the best of their ability on the serial addition task, while making sure to study the words appearing on the screen in front of them. No other stimuli than the study words were presented during the single-task study list.

The word study lists for the single- and dual-task conditions were identical in form. The lists consisted of 30 high-frequency and 30 low-frequency words, blocked into two groups each of 15 high-frequency and 15 low-frequency words. Each list began and ended with 4 medium-frequency buffer items, and 4 buffer items occurred between each block of low- and high-frequency words. The blocking technique was used to prevent participants from carrying over encoding between low-frequency and high-frequency trials. Each study item was presented for 1.5 s.

Following each study list, participants played a simple video game for 5 min. At the beginning of each test list, participants were reminded of the remember–familiar instructions and asked to respond as quickly as possible while still being as accurate as possible. The two test lists both contained 60 old low- and high-frequency studied items and 60 new low- and high-frequency lures. No filler items were presented during the test list. Participants were required to respond within 4 s, at which point the word would disappear from the screen. After being tested on the first study list, participants studied the second list of items in either the dual- or single-task condition, whichever had not yet been completed.

Results and Discussion

We analyzed the results of the recognition memory test in terms of remember and familiar hits and false alarms. Figure 3A shows the remember and familiar hits. Remember hits showed a main effect for encoding task type (single vs. dual), $F(1, 27) = 36.13$, $p < .001$, and word frequency, $F(1, 27) = 7.49$, $p < .05$. Although the Task × Frequency interaction was not significant, $F(1, 27) = 3.34$, $p = .08$, the means, as shown in Figure 3A, indicate a much smaller difference between high- and low-frequency remember hits in the dual-task condition than in the single-task condition. Familiar hits also showed main effects of task, $F(1, 27) = 16.17$, $p < .001$, and word frequency, $F(1, 27) = 5.22$, $p < .05$, but no interaction, $F(1, 27) = 0.02$, $p = .89$. In this case, Figure 3A indicates approximately the same pattern for both single- and dual-task conditions, where high-frequency words produce more familiar hits than low-frequency words.

The false alarm portion of the mirror effect was also analyzed according to remember and familiar responses, as seen in Figure 3B. Remember false alarms had no main effect of task, $F(1, 27) = 0.23$, $p = .63$. However, these responses did show a main effect of word frequency, $F(1, 27) = 6.05$, $p < .05$, and an interaction of task and word frequency, $F(1, 27) = 4.94$, $p < .05$. Tukey's honestly significant difference (HSD) tests (all Tukey's tests had an alpha of .05) revealed that there were more remember false alarms to high-frequency words than to low-frequency words in the single-task condition, with no difference in the dual-task condition. Familiar false alarms showed main effects of task, $F(1, 27) = 22.14$, $p < .001$, and word frequency, $F(1, 27) = 18.35$, $p < .001$, but no interaction between those two variables, $F(1, 27) = 0.05$, $p = .82$. Familiar false alarms were greater to high-frequency words in both encoding task conditions.

Experiment 2 provides some support for our hypothesis that recollection of low-frequency words would be more harmed than high-frequency words following a divided attention encoding condition. Although the means for remember hits suggest an interaction of word frequency and encoding task condition, the statistics for this interaction only approach significance. In addition, we found a significant interaction for remember false alarms in the single- and dual-task conditions. Because we expected our manipulation to operate at encoding, it was not clear why we would see an effect for the false alarms. Experiment 3 was designed to clarify these effects, determining the replicability of the word frequency and encoding task interactions.

Experiment 3

Low-frequency words are more likely to be associated with correct source judgments than high-frequency words (Rugg, Cox, Doyle, & Wells, 1995). Source judgments ask participants to report a contextual detail from the study phase that was varied systematically. This allows the experimenter to assess whether a recollection is based on retrieval of contextual information, rather than relying on phenomenological reports alone. The low-frequency source memory advantage provides supporting evidence for the SAC account of the mirror effect by demonstrating that the hit portion of the mirror effect is driven by recollection-based responses.

Experiment 3 was designed to replicate Experiment 2, as well as to study source judgments. We collected source judgments in order to determine whether the dual-task encoding condition affected memory for contextual information. If it is true that the divided attention manipulation makes it more difficult to episodically encode low-frequency words, we should see that there is no hit rate advantage for low-frequency words in the dual-task condition. However, if low-frequency words have an advantage at retrieval when the episodic information has been successfully bound, as predicted by the SAC model, we should see that low-frequency words that are correctly remembered are more likely to be accompanied by a correct source judgment than high-frequency words that are correctly remembered.

Method

Participants—Twenty-seven students from Carnegie Mellon University participated for partial credit in their psychology classes. All participants were native English speakers. One participant produced more than 75% false alarms in all conditions and thus was dropped from the data analyses, for a total of 26 participants.

Materials—Words were selected from the MRC database (Coltheart, 1981) with 160 high-frequency words, 160 low-frequency words, and 60 medium-frequency words. The high-frequency words had an average Kučera–Francis frequency of 174, ranging from 70 to 613. The low-frequency words had an average frequency of 1.93, ranging from 1 to 3. The medium-frequency words had an average frequency of 36 and were used as buffer words. We also approximately controlled concreteness, imagability, and number of letters for the high-frequency words (432, 467, and 6.2, respectively) and low-frequency words (449, 475, and 6.1, respectively). Of the 160 high-frequency and 160 low-frequency words, 28 high-frequency and 28 low-frequency words were randomly selected for each of two lists. In addition, 24 medium-frequency words were used as buffer items on the study list. Squares of eight colors were used as backgrounds for the words: green, yellow, brown, orange, purple, red, blue, and pink.

Procedure—Participants studied two lists of words and were tested on each list immediately following the study phase. One list was studied under the same divided attention procedure used in Experiment 2, the addition task, with numbers presented every 4 s. The study lists were blocked such that each quarter of the list (20 words) was presented with the same background color. This blocking meant that the background color also indicated temporal context, thus providing more information to assist with the source judgment. There were a total of four background colors presented on each list. Within each background color block, one block of high-frequency and one block of low-frequency words were presented, with seven words in each block. All blocks were separated by two untested medium-frequency buffer words presented in the same background color. The background colors were randomly assigned, and the block orders were counterbalanced.

Half of the participants studied the dual-task list first, and half studied the single-task list first. All participants practiced the secondary task before beginning any study lists. Participants were instructed to try to remember both the word and the background color with which it was presented. All words were studied for 2.5 s.

Immediately following each study list, a test list was presented. The test lists consisted of 28 old high-frequency words, 28 old low-frequency words, and 28 new words from each frequency category. Participants were asked to respond either “old” or “new” to each word in the test phase. If the participant responded “new,” a 500-ms pause occurred before the next test word. For “old” responses, participants were asked to indicate which background color was presented with the word. They were given a list of the four background colors that were presented on that list. If they could not remember the background color, they were able to skip the source judgment without making a response.

Results and Discussion

Figure 4 shows the mean hits and false alarms for low- and high-frequency words in the single-task and dual-task encoding conditions. Hits were analyzed using a 2 × 2 repeated measures analysis of variance (ANOVA). The test revealed a main effect of encoding task, $F(1, 25) = 28.89$, $p < .001$. The main effect of word frequency was not significant, $F(1, 25) = 3.17$, $MSE = .012$; however, the interaction of encoding task and word frequency was significant, $F(1, 25) = 5.94$, $p < .05$. Tukey's HSD tests ($\alpha = .05$) indicated that low-frequency words produced significantly more hits than high-frequency words following the single-task encoding condition but that there was no difference in hits between the high-and low-frequency words following the dual-task encoding condition. A second repeated measures ANOVA was used to examine the false alarm effects. Main effects of encoding task, $F(1, 25) = 11.89$, $p < .01$, and word frequency, $F(1, 25) = 33.32$, $p < .001$, were significant. There was no reliable interaction between encoding task and word frequency, $F(1, 25) = 0.32$, $MSE = .009$.

Source memory judgments are presented in Figure 5, as raw number correct and incorrect for old items of each list and word frequency category.[1] The mean numbers of “don't know” responses for the dual low-frequency, dual high-frequency, single low-frequency, and single high-frequency conditions were 2.46, 3.31, 3.19, and 3.31, respectively. A 2 × 2 repeated measures ANOVA for the correct source judgments revealed main effects of both encoding task condition, $F(1, 25) = 42.52$, $p < .001$, and word frequency, $F(1, 25) = 6.35$, $p < .05$. There

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[1] We chose to report raw numbers rather than proportions for the source memory task as proportions would be influenced by the number of trials on which participants chose to say they did not remember the source and thus could not make a correct or incorrect judgment.

was no Task × Frequency interaction, $F(1, 25) = 3.47$, $MSE = 4.07$. Incorrect source judgments were also analyzed, but no significant main effects or interactions were found (all *F*s < 1).

Experiment 3 replicated the key interaction found in Experiment 2. That is, a significant encoding task by frequency interaction occurred in the hits. For this experiment, the post hoc comparisons indicated that there was a significant advantage for low-frequency words in the single-task condition, but that advantage did not occur in the dual-task condition. We found no interaction in the false alarms. The pattern of “old” false alarms seen in Experiment 3 was similar to the pattern of “familiar” false alarms seen in Experiment 2. High-frequency words showed a disadvantage in both the single- and dual-task conditions, with more false alarms occurring overall in the dual-task condition.

The source memory task showed a low-frequency advantage for recalling contextual details of the study episode in both the single-and dual-task encoding conditions. It is important to note that these source judgments were made only when the participant indicated that the item was seen on the list, and we analyzed only those source judgments that were made for items that were actually old. Therefore, the source analysis reflects trials on which the participant correctly remembered the word. This finding fits nicely with our claim of encoding–retrieval tradeoffs in the word frequency effect. Low-frequency words were more harmed by a dual-task manipulation than high-frequency words. However, when the words were correctly remembered and thus episodically encoded, low-frequency words produced more accurate source memory, indicating that they were more likely to be recollected.

Experiment 4

Experiments 2 and 3 established that a divided attention manipulation at encoding removed the hit rate advantage for low-frequency words in recognition. Experiment 3 established that low-frequency words still showed a source memory advantage over high-frequency words when correctly remembered. However, it could be argued that the reduction in the hit rate advantage for low-frequency words is due to an overall reduction in recognition and thus that the interaction is actually due to a scale effect (Loftus, 1978). To test our hypothesis of a low-frequency encoding disadvantage without the contamination of scale changes, we chose to extend Experiment 1 by demonstrating that the presence of a low-frequency word during encoding reduces memory for other low-frequency words as well as high-frequency words. We tested this hypothesis by using a paradigm in which participants studied two items at the same time but were tested on those items separately. This also allowed us to examine the effects of low-frequency words at encoding in conditions where the retrieval advantage should be equal at test.

Two prior experiments have attempted to determine whether the presence of low-frequency words at study reduces memory for other stimuli and have found conflicting results. One study did not find any effect of the presence of a low-frequency word at study on hit rate (Gillund & Shiffrin, 1984). A separate study that required encoding of three words simultaneously found that the low-frequency hit rate advantage was reversed at encoding times of less than 2.5 s (Clark & Shiffrin, 1992). With the current study we attempt to clarify whether low-frequency words can reduce memory for a second word presented simultaneously.

Method

Participants—Twenty-three Carnegie Mellon University students participated, for either partial fulfillment of course research requirements or $10 payment.

Materials—The same words were used in Experiments 3 and 4. Two study lists were constructed for each participant by randomly grouping 20 high-frequency words into 10 pairs, 20 low-frequency words into 10 pairs, and 10 of each type into 10 mixed-frequency pairs. The lists were blocked by pair type—high-frequency pure, mixed, and low-frequency pure—with two medium-frequency filler pairs used as buffers between each block and at the beginning and end of the lists. Test lists were made by presenting the 60 old items individually along with 30 new high-frequency and 30 new low-frequency words.

Procedure—Participants studied two lists of words and were tested on each list immediately following the study phase. Each participant was randomly assigned to study either the dual-task (as used in Experiments 2 and 3) or single-task list first. All participants studied one list of each type. All participants practiced the secondary task before beginning any study lists. Participants were instructed to try to study both words equally as they would be tested on both words individually. All word pairs were studied for 1.8 s. Immediately following each study list, a test list was presented. Participants were asked to respond either “remember,” “familiar,” or “new,” according to the same instructions as used in Experiment 2.

Results and Discussion

Responses were analyzed according to encoding task condition, word frequency, and response type. Figure 6A shows the remember hits for both the single- and dual-task conditions. The dual-task condition was at floor (remember hits, M = 12%; remember false alarms, M = 8%), and thus we did not analyze those responses. For the parameters of this experiment, participants were unable to effectively study both words in the given amount of time under divided attention conditions.

A 2 × 2 ANOVA was used to analyze the remember hits in the single-task condition (remember hits, M = 44%; remember false alarms, M = 9%). This ANOVA revealed a significant main effect of word frequency, $F(1, 22) = 25.86$, $p < .001$, such that low-frequency words produced more remember hits overall than high-frequency words. There was no main effect of pair type (pure vs. mixed), $F(1, 22) = 0.06$, $MSE = .022$. The interaction of word frequency by pair type was significant, $F(1, 22) = 6.10$, $p < .05$. Follow-up Tukey's HSD tests ($\alpha = .05$) indicated that there were more remember hits given to low-frequency words studied in mixed pairs than high-frequency words studied in mixed pairs but that there was no difference between high- and low-frequency words studied in pure pairs. Paired-samples t tests conducted on the false alarm rates, as seen in Figure 7, revealed that there were more remember false alarms to high-frequency words in both the dual-task, $t(22) = 2.67$, $p < .05$, and single-task conditions, $t(21) = 2.40$, $p < .05$.

Familiar hits are shown in Figure 6B, and familiar false alarms are shown in Figure 7. Both the dual-task and single-task familiar responses seemed to be at floor (dual-task hits, M = 29%; dual-task false alarms, M = 29%; single-task hits, M = 26%; single-task false alarms, M = 25%). To remain consistent with the remember response analysis, we analyzed the single-task performance with a 2 × 2 repeated measures ANOVA. The only significant effect was a main effect of frequency, such that high-frequency words produced more familiar hits on the single-task list than low-frequency words, $F(1, 22) = 11.26$, $p < .01$. The false alarms were analyzed with t tests, revealing more familiar false alarms for high-frequency words than for low-frequency words in both the dual-task, $t(22) = 2.48$, $p < .05$, and single-task, $t(22) = 4.28$, $p < .001$, conditions.

The results of Experiment 4 support our claim that low-frequency words require more attention during encoding than high-frequency words. Although participants were instructed to study both words in the presented pair equally, their memory for both high- and low-frequency words was reduced when the paired word was low frequency. Thus, high-frequency words received more hits when paired with another high-frequency word, in the pure condition, and low-frequency words received more hits when paired with a high-frequency word, in the mixed condition. We were unable to interpret the results of the dual-task manipulation, given that participants produced near chance performance in all conditions following a divided attention manipulation at encoding.

General Discussion

We hypothesized that word frequency effects in recognition have two components. Previous research has shown that low-frequency words are more likely to be recollected than high-frequency words. The SAC model argues that this is due to an advantage for low-frequency words at retrieval (Reder et al., 2000). Other models and studies have concluded that low-frequency words receive more attention at encoding (Glanzer & Adams, 1990; Malmberg & Nelson, 2003; Naveh-Benjamin et al., 1998; Naveh-Benjamin & Guez, 2000). It is important to note that the retrieval advantage described in SAC cannot occur unless encoding processes are sufficient to allow low-frequency words to be bound to episodic information. We propose that low-frequency words require more attention during encoding to achieve this episodic binding than do high-frequency words. The experiments described in the current article provide evidence that low-frequency words are more difficult to encode than high-frequency words. This increased burden to encode low-frequency words can be manifested either as a reduction in ability to encode simultaneously presented stimuli or as a greater cost to recognition accuracy for low-frequency words as compared with high-frequency words following dual-task encoding conditions.

It could be argued that our experimental results do not rule out the possibility that the low-frequency advantage in recognition is caused solely by increased attention at study. This hypothesis would also mean that there is no retrieval advantage for low-frequency words in recognition. However, our Experiment 3 contradicts this claim to some degree. Experiment 3 demonstrates that reducing processing resources during encoding reduces memory for low-frequency words more than for high-frequency words but that for those words that are successfully encoded, source memory is better for low-frequency words than for high-frequency words. An explanation that claims that the low-frequency hit rate advantage is due solely to increased attention at encoding would not predict that source memory would be better in the condition where divided attention prevents the hit rate advantage from occurring. In addition, previous studies have shown that the effects of contextual frequency, which have the same mechanism that is proposed in SAC for frequency effects, operate at retrieval (Park, Arndt, & Reder, in press).

Another alternative explanation for our findings is that the divided attention manipulation reduces episodic encoding overall and thus reduces memory for low-frequency words to a greater degree because they rely on recollection to a greater degree than high-frequency words. Yonelinas (2001) found that reduced attention during encoding reduced remember responses as well as know responses, although remember responses showed a larger effect. Similar studies have found that the primary impairment occurs in the recollection process (Gardiner & Java, 1990; Gardiner & Parkin, 1990; Parkin, Gardiner, & Rosser, 1995; Reinitz, Morrissey, & Demb, 1994). Our Experiments 1 and 4 provide evidence against this explanation. It is unlikely that the presence of a low-frequency word at study reduced use of the recollection process overall, as may have occurred in Experiments 2 and 3. If anything, the presence of a low-frequency word had a larger decrement on performance for high-frequency words in Experiment 4. Therefore this reduced recollection explanation cannot predict the results of Experiments 1 and 4.

Although a case could be made for either of these alternative explanations, we feel that the experiments presented here, along with prior research findings, support the claim that low-frequency words both require more attention to be encoded and are more likely to be recollected at retrieval, owing to having fewer episodic associations. Given prior studies of encoding time (Hirshman & Palij, 1992; Malmberg & Nelson, 2003), which have indicated that the low-frequency hit rate advantage is removed only at very short encoding times, we conclude that the increased attention necessary at encoding must be required for early stages of encoding. However, once that initial minimum encoding takes place, additional encoding time does not improve recognition further. The findings from encoding time studies fit with our claim that low-frequency words require enough attention to be bound to the episodic context but that this minimum encoding is all that is required in order to allow the retrieval advantage to operate on the episode node. If the low-frequency hit rate advantage were due entirely to additional attention at encoding, presumably further attention at later stages of encoding would increase this advantage.

A similar hypothesis to our contention that encoding is more difficult for low-frequency words was previously proposed by DeLosh and McDaniel (1996) with regard to findings in the recall literature. Their order-encoding hypothesis argued that low-frequency words reduce the encoding of order information by drawing processing resources to encoding of the idiosyncratic features of individual low-frequency items. This hypothesis explained why high-frequency words on a pure list were better recalled than high-frequency words on a mixed list, whereas low-frequency words were better recalled on a mixed list than on a pure list. This finding is similar to the finding seen in our Experiment 4. The order-encoding hypothesis differs from our claim in that we would not limit the encoding deficit to order information alone (which is less crucial for recognition tasks) but rather would claim that episodic information in general, encompassing order information, is more difficult to encode for low-frequency words. This additional assumption extends their order-encoding hypothesis to account for findings in tasks other than recall.

Conclusion

Our findings support the hypothesis that word frequency affects both the encoding and retrieval stages of memory in a recognition task. Although low-frequency words require more attention to be bound to the episodic context, successfully bound low-frequency items are more easily recollected than successfully bound high-frequency items. If we assume that low-frequency words do require more attention at encoding, this may explain why high-frequency words are better remembered in nonrecognition memory tasks such as recall, cued recall, and associative recognition.

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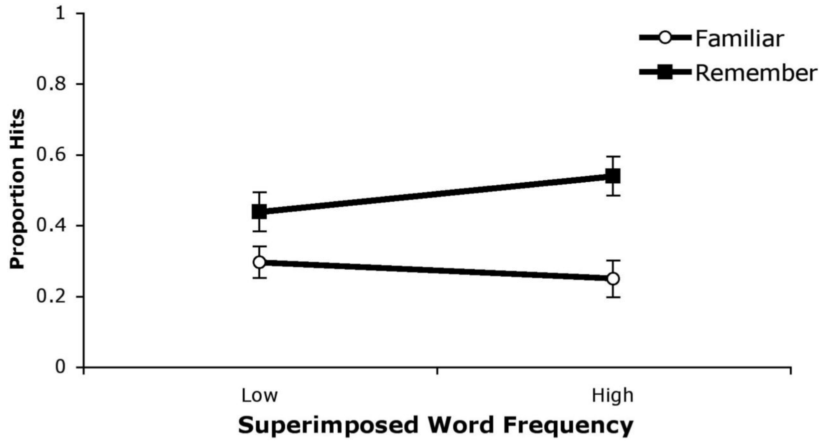

Figure 1.
Remember and familiar hits for the picture recognition test as a function of superimposed word frequency at study in Experiment 1. Error bars indicate the standard error.

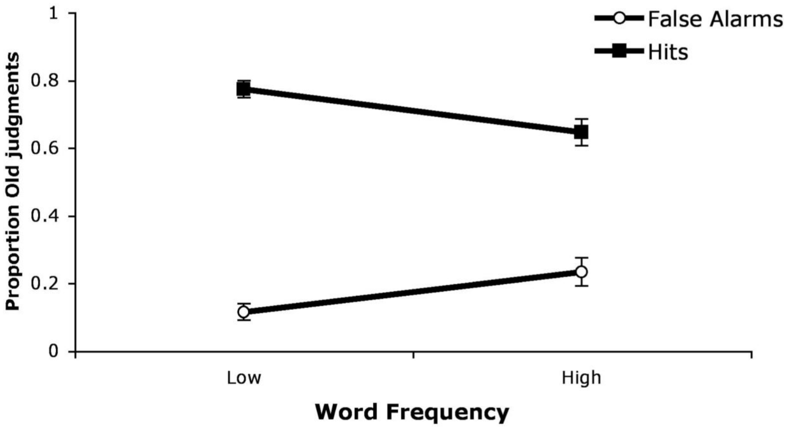

Figure 2.
Hits and false alarms for the word recognition test as a function of word frequency in Experiment 1. Error bars indicate the standard error.

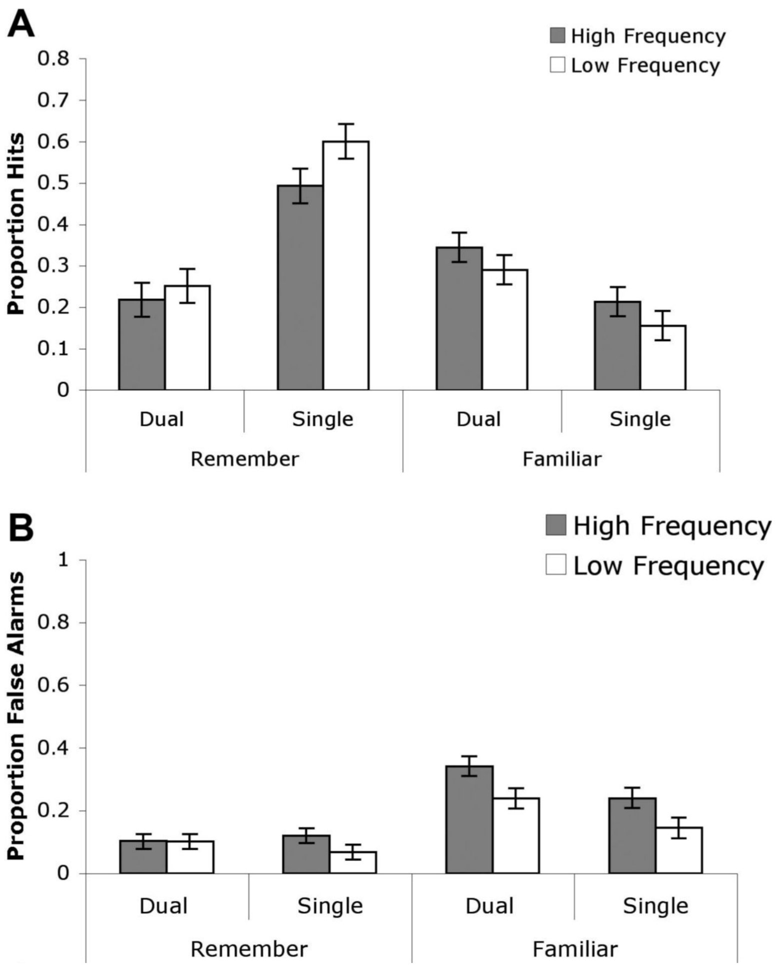

Figure 3.
Remember and familiar hits and false alarms as a function of word frequency and task condition for Experiment 2. Panel A shows hits, and Panel B shows false alarms. Error bars indicate the standard error.

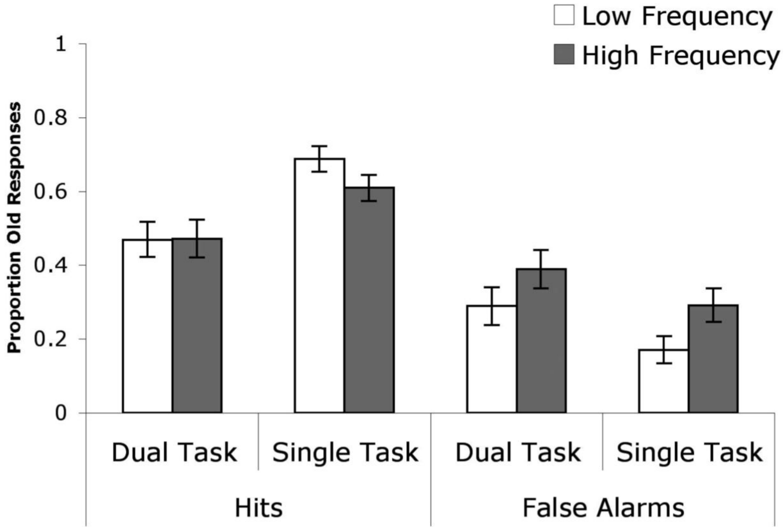

Figure 4.

Hits and false alarms for Experiment 3 as a function of word frequency and task condition. Error bars indicate the standard error.

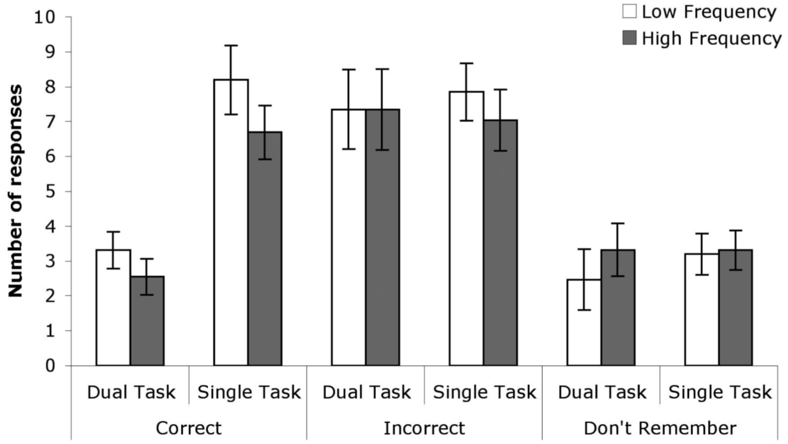

Figure 5.

Raw number of correct, incorrect, and “don't remember” responses on the source judgment task by word frequency and encoding condition. Error bars indicate the standard error.

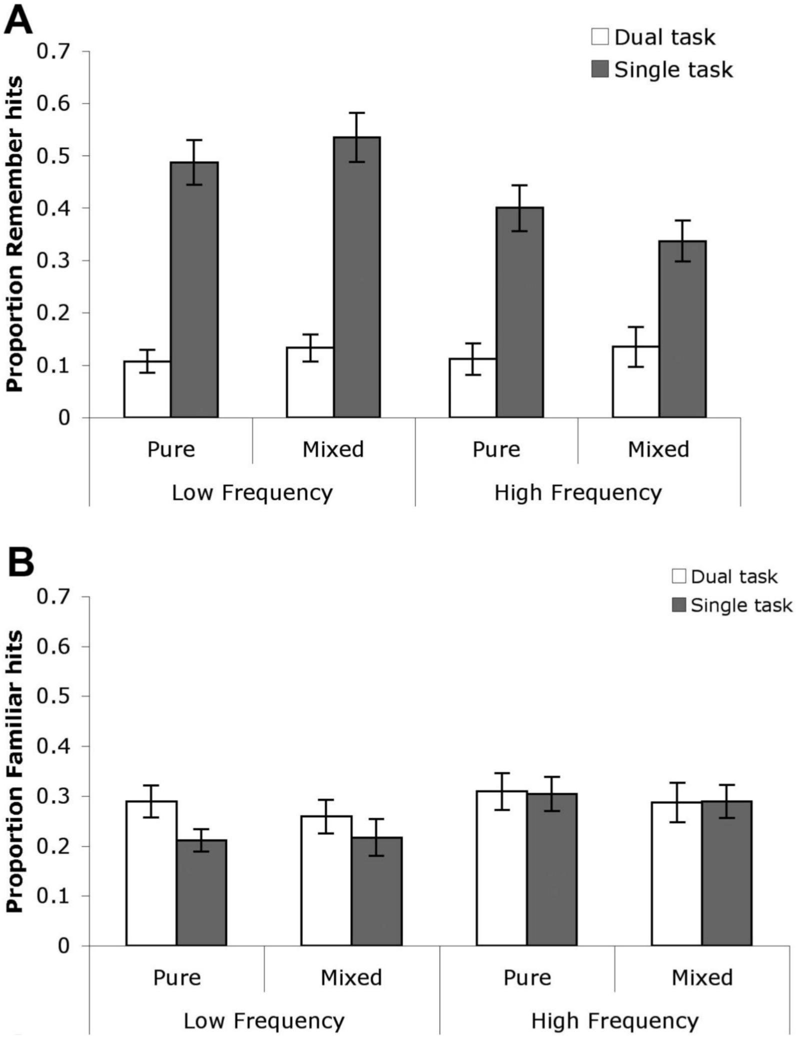

Figure 6.

Proportion of remember and familiar hits. Panel A shows remember hits, and Panel B shows familiar hits. Error bars indicate the standard error.

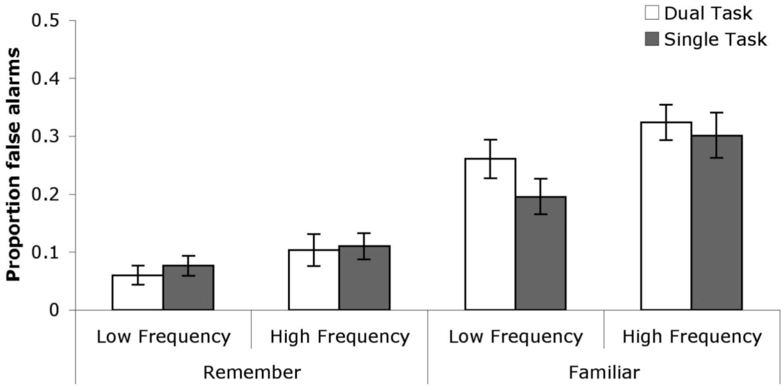

Figure 7.

Proportion of remember and familiar false alarms by word frequency and task encoding condition. Error bars indicate the standard error.