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Left-frontal brain potentials index conceptual implicit memory for words initially viewed subliminally

Jason C.W. Chen[a,b,*,1], *Wen Li*[b,c,2], *Ming Lui*[b,3], *Ken A. Paller*[b,c]

[a]*Laboratory for Cognitive Neuroscience, Institute of Neuroscience, National Yang-Ming University, Taiwan*
[b]*Department of Psychology, Northwestern University, Evanston, Illinois, USA*
[c]*Interdepartmental Neuroscience Program, Northwestern University, Evanston, Illinois, USA*

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ABSTRACT

Neural correlates of explicit and implicit memory tend to co-occur and are therefore difficult to measure independently, posing problems for understanding the unique nature of different types of memory processing. To circumvent this problem, we developed an experimental design wherein subjects acquired information from words presented in a subliminal manner, such that conscious remembering was minimized. Cross-modal word repetition was used so that perceptual implicit memory would also be limited. Healthy human subjects viewed subliminal words six times each and about 2 min later heard the same words interspersed with new words in a category-verification test. Electrophysiological correlates of word repetition included negative brain potentials over left-frontal locations beginning approximately 500 ms after word onset. Behavioral responses were slower for repeated words than for new words. Differential processing of word meaning in the absence of explicit memory was most likely responsible for differential electrical and behavioral responses to old versus new words. Moreover, these effects were distinct from neural correlates of explicit memory observed in prior experiments, and were observed here in two separate experiments, thus providing a foundation for further investigations of relationships and interactions between different types of memory engaged when words repeat.

1. Introduction

A prominent focus in contemporary memory research concerns the characterization of *implicit memory* as a special type of memory wherein past experience influences a person's behavior without his or her conscious awareness of that influence (Gabrieli, 1998; Roediger and McDermott, 1993). Typical tests used to evaluate implicit memory for words (e.g., the lexical-decision test, the stem completion test, and the category-verification test) often face the challenge of contamination by explicit remembering of prior events that can occur concurrently with implicit memory (Richardson-Klavehn and Bjork, 1988). To circumvent this concern, we investigated memory for subliminally presented words. Furthermore, recordings of EEG responses were included to allow us to search for neural correlates of *conceptual implicit*

* *Corresponding author*. K4/822 Clinical Science Center, 600 Highland Ave., Madison, WI 53792, USA.
E-mail address: j.chen@neurosurg.wisc.edu (J.C.W. Chen).
[1] Currently at the Department of Neurological Surgery, University of Wisconsin-Madison, USA.
[2] Currently at the Department of Psychology, University of Wisconsin-Madison, USA.
[3] Currently at the Institute of Cognitive Neuroscience, National Central University, Taiwan.

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memory—which is implicit memory for recently encountered conceptual information.

The possibility that information perceived without awareness can influence human behavior and brain activity has attracted much investigation by cognitive psychologists and neuroscientists (Dehaene et al., 2006; Diaz and McCarthy, 2007; Elliott and Dolan, 1998; Gaillard et al., 2007; Greenwald et al., 1996; Hannula et al., 2005). A widely used method to preclude conscious awareness of perceived information is to use brief visual presentations with backward masking (Greenwald and Draine, 1998; Marcel, 1983). Such methods have yielded reliable *subliminal priming effects* in various domains, including social judgments (Fazio, 2001; Li et al., 2008), monetary decisions (Pessiglione et al., 2007), and lexical/semantic judgments (Kiefer and Spitzer, 2000; Sergent et al., 2005). Many of these subliminal priming effects are primarily conceptual or semantic in nature, in that they are likely mediated through facilitated processing of meaning as opposed to perceptual features of stimuli. For example, preference judgments made to faces were altered in accordance with the valence of immediately preceding odor stimuli that were pleasant or unpleasant and that were presented in a subliminal manner (Li et al., 2007a). In another study, behavioral and neural responses in the task of deciding whether a supraliminal digit was greater or smaller than five were altered by subliminal stimuli (Dehaene et al., 1998). Facilitation was found when a congruent subliminal numeral preceded the digit (e.g., subliminal 'NINE,' then '6') compared to when an incongruent subliminal numeral preceded the digit (e.g., subliminal 'ONE,' then '6'). Nevertheless, the use of very brief intervals between subliminal items and subsequent targets in these studies raises questions about the durability of these effects. In other words, it is unclear if subliminal information would produce memory that has reasonable persistence—lasting for seconds, minutes, or even longer—as in typical studies of conceptual implicit memory (e.g., Levy et al., 2004; Meister et al., 2007; Roediger et al., 2007; Schacter and Buckner, 1998; Vaidya et al., 1997).

In our studies, we examined effects of viewing subliminal words with an interposed delay. Words were shown on a computer screen in a subliminal manner, and 2 min later, a category-verification test was administered using the same words (*old words*) intermixed with a matched and counterbalanced set of words that had not been shown earlier (*new words*). These old and new test words were delivered in the auditory modality, so that we could rule out perceptual memory effects and potentially isolate conceptual memory effects. Evidence for conceptual implicit memory can thus be obtained in this paradigm if behavioral responses in the category-verification test differ for old words compared to new words.

We describe two experiments using this behavioral paradigm, both completed with concurrent recordings of event-related potentials (ERPs). Although some prior experiments have examined effects of viewing subliminal words on subsequent stimulus processing and ERPs (e.g., Holcomb et al., 2005; Kiefer and Spitzer, 2000; Marzouki, Midgley, Holcomb, Grainger, 2008; Misra and Holcomb, 2003; Schnyer et al., 1997, 1999), such experiments have seldom been run with interposed retention intervals following subliminal stimulus pre-

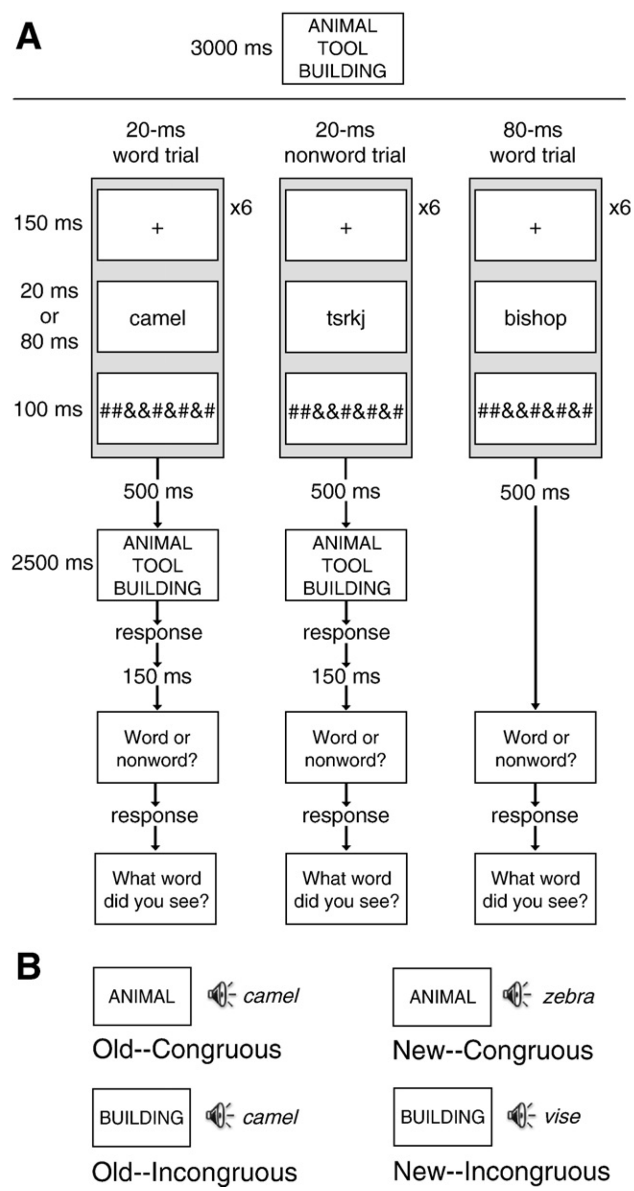

Fig. 1 – Stimulus events during study phase and test phase. (A) Three categories were used in each run and were presented together at the start of the study phase. Each run included six 20-ms word trials, three 20-ms nonword trials, and two 80-ms word trials. Each 20-ms trial included six successive presentations of fixation cross, word, and mask, followed by the three categories for the category-matching task, wherein participants attempted to select the category of the masked word on each trial. Participants then made a lexical decision and attempted to pronounce the masked word. Essentially identical procedures were used in Experiment 2 except that the three category names shown in category-matching task did not correspond to the masked words. (B) In the test phase, participants made speeded responses to the simultaneous presentation of a visual category name and an auditory exemplar. Each test phase included 12 trials. Half included a word studied in the prior study phase and half included a new word.

sentations. Given the absence of strong predictions about the specifics of conceptual implicit memory for stimuli viewed only subliminally, replication of the findings in two separate experiments was essential.

In Experiment 1, memory effects were examined using 20 study-test blocks. In the study phase of each block (Fig. 1A), subjects viewed a set of six words shown subliminally. Each word was shown six times in succession, each time for 20 ms and backward masked by a string of symbols. The sixth presentation was followed by three category names. Subjects attempted to choose the one category that matched the subliminal word. This test provided an assessment of the processing of the subliminal word and also served to encourage relevant conceptual processing during the study phase. The study phase also included two additional trial types. In 80-ms word trials, the procedure was the same except that a longer duration for the sixth word presentation made it easier to read. The inclusion of this trial type functioned to keep subjects actively attending to subliminal words. In 20-ms nonword trials, a nonword was shown six times. Subjects were asked to make lexical decisions on every trial so that we could assess their ability to distinguish 20-ms words from 20-ms nonwords. In the test phase of each block (Fig. 1B), subjects viewed a sequence of category names, each accompanied by a spoken word, and performed a category-verification test that required a binary decision concerning whether the word fit into the category. This procedure allowed us to analyze behavioral and ERP responses as a function of whether the spoken words had or had not been viewed in the prior study phase.

2. Results

2.1. Experiment 1

2.1.1. Study-phase behavior

We established the absence of conscious perception of 20-ms words during the study phase using three different approaches. Firstly, performance in the forced-choice category-matching test revealed that participants as a group were at exactly the level expected based on random guessing, accuracy = 0.33 (*SE* = 0.04; range, 0.27 to 0.41), and individually, every subject fell within the range of the 95% threshold on the binomial distribution (0.25 to 0.41), suggesting that none of them was able to perform significantly better than chance.

Secondly, performance in the lexical-decision task showed an inability to discriminate between 20-ms words and 20-ms nonwords. For each participant, a *lexical discrimination score* was computed as the hit rate for correctly endorsing 20-ms words as words minus the false-alarm rate for incorrectly endorsing 20-ms nonwords as words, yielding a mean of 0.01 (*SE* = 0.03) that was not significantly different from 0 [$t(15) < 1$].

Thirdly, participants were largely unable to produce 20-ms words when requested to do so on each trial in the study phase. On 76.6% of the trials (*SD* = 7%; range, 64% to 78%), participants failed to produce any word. On the remaining trials, they produced a word that was seldom the correct word. Considering the 1,920 trials in the experiment (i.e., 120 trials for each of 16 participants), the correct word was produced only 0.9% of the time (17 of all these trials), and these trials were excluded from all analyses. For 11 of the 16 participants, none of the 20-ms words were correctly produced.

To ensure that participants were allocating sufficient effort to these assigned tasks, we examined their performance on the 80-ms word trials. The mean lexical discrimination score was 0.36 (hit rate for 80-ms words minus false-alarm rate for 20-ms nonwords, *SE* = 0.05), which was significantly higher than the 0.01 score for 20-ms words [$t(15) = 4.79$, $p < 0.001$]. In addition, participants produced the correct word 68.5% of the time (*SD* = 12%; range, 53% to 80%).

2.1.2. Test phase behavior

As shown in Fig. 2, we observed an effect of subliminal word presentation in the form of slower responses for trials with old words than for those with new words [$F(1,15) = 5.98$, $p < 0.05$]. The overall mean difference in reaction time was 19 ms (*SE* = 20). There was also a nonsignificant trend for slower category-verification responses on incongruous than on congruous trials [$F(1,15) = 3.25$, $p = 0.09$], and a nonsignificant repetition-by-congruity interaction [$F(1,15) = 2.64$, $p > 0.1$].

Accuracy for incongruous trials was significantly higher than that for congruous trials [$F(1,15) = 57.07$, $p < 0.001$], presumably reflecting participants' tendency to judge category-exemplar pairs as incongruous, such as when they were unsure of uncommon exemplars (e.g. *TREE-ginkgo*). Repetition did not influence category-verification accuracy [$F(1,15) < 1$], and the repetition-by-congruity interaction was nonsignificant [$F(1,15) < 1$].

These results show that subliminal presentations altered the way corresponding conceptual information was processed about 2 min later. Unlike previous findings that immediate priming of conceptual information yielded facilitated responses (e.g., Kiefer and Spitzer, 2000; Schnyer et al., 1997), these subliminal presentations slowed down category verification. This divergence may be related to various aspects of the current paradigm, including the longer retention interval

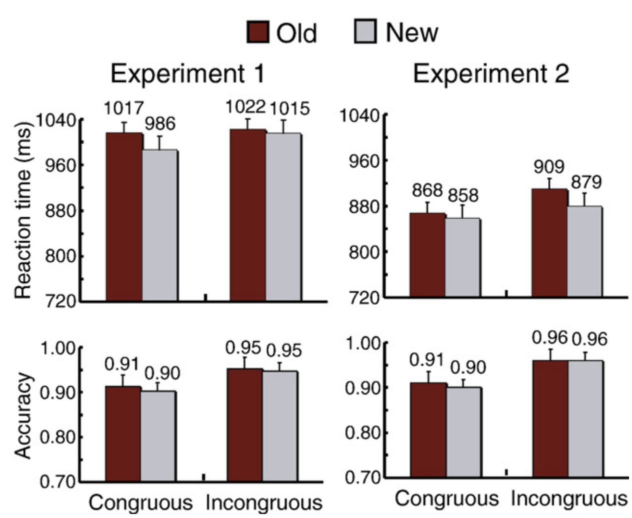

Fig. 2 – Behavioral results from test phase. Upper panels show that reaction times in the category-verification test were slower on trials with old words than on trials with new words. Lower panels show that accuracy did not differ.

between study items and test items. Also, most previous studies that have found speeded lexical decisions or categorization decisions following word repetition employed supraliminal word presentations; it is possible that subliminal word presentations produce qualitatively different repetition effects, as discussed further below. The 19-ms slowing of mean reaction time for old words compared to new words was not expected, and thus it was interpreted tentatively and considered in need of replication (see Experiment 2).

2.1.3. *Test phase ERPs*

Whereas congruity effects on ERPs were expected on the basis of the N400 literature (Kutas et al., 2006), we did not hold firm predictions about ERP correlates of word repetition. The congruity effects were clear-cut, as ERPs appeared more negative for incongruous trials than for congruous trials at many scalp locations. For example, in the interval from 400 to 800 ms the mean amplitude at the central midline location was −2.13 μV on congruous trials and −4.51 μV on incongruous trials [$t(15)=5.22$, $p<0.001$]. More central to the goals of the present experiment, ERP traces of subliminal word presentation were apparent as larger negative brain potentials on trials with old versus new words. As shown in Fig. 3, this repetition effect was visible as a left-frontal negativity beginning about 500 ms after word onset.

To quantify ERP results in the absence of specific a priori predictions, given the absence of prior ERP findings for cross-modal repetition following subliminal word presentations, we conducted exploratory analysis on ERPs from four midline scalp regions (frontal, central, parietal, and occipital) and four lateral scalp regions (left/right frontal and left/right temporal), as shown in Fig. 3. Mean amplitudes were measured over 100-ms intervals from 300 to 900 ms. A Greenhouse–Geisser correction was applied for all repeated measures that had more than one degree of freedom in the numerator. Adjusted degrees of freedom and *p*-values are reported. Generic analyses were guided by an omnibus repeated-measures analysis of variance (ANOVA).

For midline ERP recordings, an ANOVA with four independent variables (repetition, congruity, region, and interval) yielded a significant four-way interaction [$F(2.67,40.05)=6.54$, $p<0.005$] and a congruity main effect [$F(1,15)=42.34$,

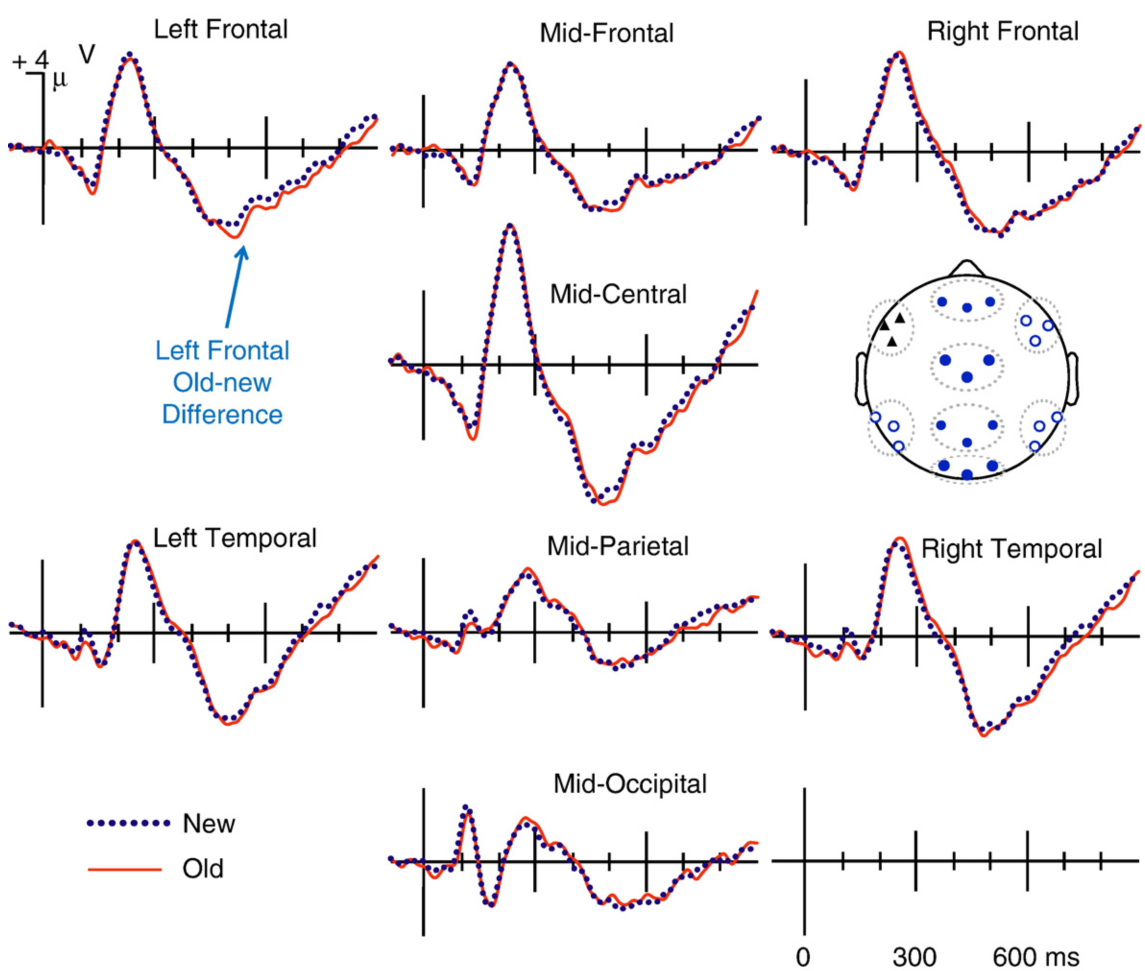

Fig. 3 – ERP repetition effects from the test phase of Experiment 1. ERPs are compared for trials with old words (solid trace) versus trials with new words (dotted trace), collapsing across congruous and incongruous trials. Waveforms were averaged across groups of electrodes, as shown in the inset view of the head as viewed from above. There were four midline electrode groups (filled circles) and four lateral electrode groups (open circles, except for triangles showing the left-frontal group). Time 0 corresponds to the simultaneous onset of the visual category and the auditory word.

$p<0.001$], along with a congruity-by-interval interaction [$F(3.10,46.59)=22.78$, $p<0.001$]. No other effects involving repetition were significant, and further analyses to follow-up the four-way interaction were uninformative (e.g., repetition main effects and repetition-by-region interactions were nonsignificant at all 100-ms intervals from 300 to 900 ms).

For lateral ERP recordings, the repeated-measure analysis with four factors (repetition, congruity, region, and interval) yielded a significant four-way interaction [$F=(5.49, 86.86)=2.11$, $p<0.05$], along with a repetition-by-time interaction [$F(3.45,51.82)=5.82$, $p<0.005$], and a congruity-by-time interaction [$F(2.95,44.22)=4.89$, $p<0.001$]. We therefore conducted separate two-way ANOVAs (repetition, region) for each 100-ms interval. At 500–600 ms, a repetition-by-region interaction emerged [$F(1.94,29.10)=5.19$, $p<0.05$], and a post-hoc paired t-test showed a significant left-frontal amplitude difference [$t(15)=2.10$, $p=0.049$]. Repetition main effects for each 100-ms interval were nonsignificant [$Fs<1$].

To further examine these putative ERP correlates of word repetition, we investigated the correlation between left-frontal amplitude differences and the accuracy of study-phase category matching. The analysis of category-matching accuracy above provided no evidence that conceptual information was extracted from words presented subliminally. However, by choosing one category (even randomly) to match the subliminal word, participants might have activated associations between the word and the category, contributing to the various effects observed in the test phase. If so, higher accuracy at study might be associated with larger behavioral or ERP effects at test. Correlations between study-phase category-matching accuracy and subsequent category-verification speed and accuracy were not statistically significant ($r=0.26$, $p>0.1$ and $r=0.18$, $p>0.1$, respectively). On the other hand, study-phase category-matching accuracy was positively correlated with left-frontal ERP effects (old-minus-new mean amplitude at 500–600 ms; $r=0.65$, $p<0.01$). This correlation indicates that ERP repetition effects may have been related to study-phase conceptual processing. To examine this possibility, it would helpful to determine if left-frontal ERP differences would be found in a design that limited contributions from the category-matching task in the study phase (see Experiment 2).

Although the left-frontal repetition effect found in Experiment 1 was not predicted in advance, prior fMRI studies have found left-prefrontal activations in association with conceptual implicit memory, as produced in semantic judgments on verbal stimuli or namable objects (Demb et al., 1995; Donaldson et al., 2001; Schacter and Buckner, 1998; Thompson-Schill et al., 1997). However, given the novelty of this design, the exploratory statistical analyses of the ERP effects, the small magnitude of left-frontal ERP effects, and the unusual behavioral results, conclusions from Experiment 1 alone must be tentative.

Therefore, we conducted a second experiment in an independent sample using an essentially identical protocol. One change in the design was that the categories presented in the study phase never matched any of the masked words, such that there was no opportunity for participants to select the correct category and so influence results in the test phase. Experiment 2 was also run with a specific prediction to guide ERP analyses—that a left-frontal ERP repetition effect would be produced in the test phase for old words compared to new words. Consistent results across the two experiments would lend support to the conclusion that the behavioral and electrophysiological measures reflect conceptual effects of cross-modal subliminal word repetition.

2.2. Experiment 2

2.2.1. Study-phase behavior

In accord with Experiment 1, behavioral data obtained in Experiment 2 showed negligible evidence of conscious awareness for 20-ms words based on measures obtained in the study phase. For category matching, estimation of accuracy was not applicable because 20-ms words did not match any of the three categories. Lexical decision accuracy indicated an inability to discriminate between 20-ms words and 20-ms nonwords, given that the mean lexical discrimination score was −0.04 ($SE=0.03$), which was not significantly different from 0 [$t(15)<1$].

Participants were largely unable to produce the 20-ms words shown in the study phase. On 78.8% of the trials ($SD=11\%$; range, 64% to 82%), participants failed to produce any word. Across all 20-ms word trials, they produced a word that was the correct word only 0.4% of the time, and these 7 trials were excluded from all analyses. For 11 of the 16 participants, none of the 20-ms words were correctly produced.

Results for 80-ms trials showed that participants were allocating sufficient effort to the assigned tasks. The mean lexical discrimination score was 0.34 ($SE=0.04$), which was significantly higher than the −0.04 score for 20-ms words [$t(15)=5.76$, $p<0.001$]. When attempting to read the 80-ms words, participants identified the correct word 62.5% of the time ($SD=13\%$; range, 50% to 85%).

2.2.2. Test phase behavior

We replicated the influence of word repetition on reaction-time measures of category-verification responses. Repetition effects following subliminal presentations were observed in the form of slower category-verification responses for old than for new words [$F(1,15)=5.00$, $p<0.05$], as shown in Fig. 2B. Responses were reliably slower for incongruous trials than for congruous trials [$F(1,15)=10.05$, $p<0.01$]. The interaction between repetition and congruity was not significant [$F(1,15)<1$].

Accuracy in the category-verification test was not significantly affected by repetition [$F(1,15)=1.44$, $p>0.1$], but it was significantly higher for incongruous than for congruous trials [$F(1,15)=16.80$, $p<0.05$]. The interaction between repetition and congruity was nonsignificant [$F(1,15)<1$].

2.2.3. Test phase ERPs

ERP findings were similar to those from Experiment 1 in several respects. As shown in Fig. 4, old words elicited larger negative brain potentials over left-frontal regions than did new words. ERPs were also more negative for incongruous than congruous trials. These N400 effects, measured at the central midline location, were significant in the interval from 400 to 800 ms [$t(15)=6.27$, $p<0.001$].

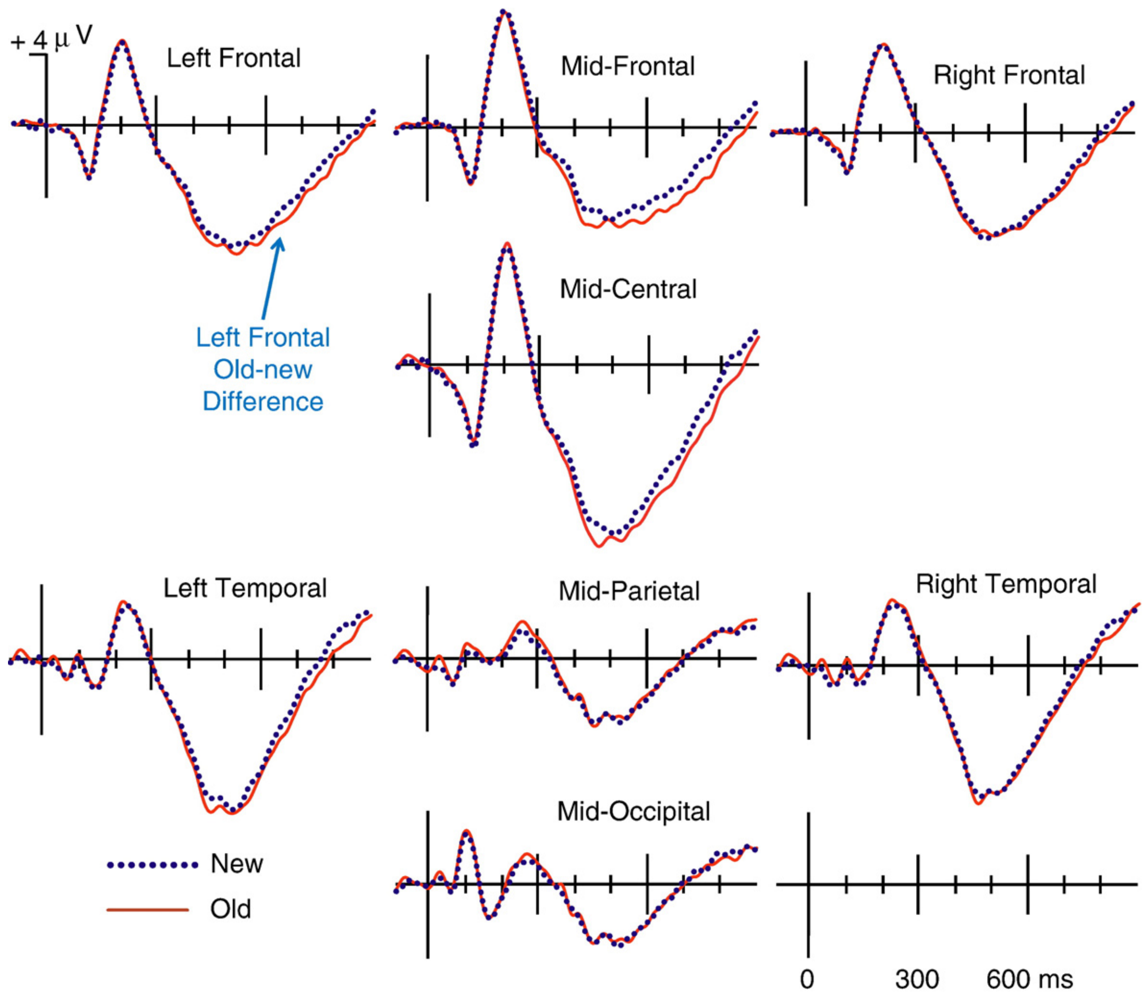

Fig. 4 – ERP repetition effects from test phase of Experiment 2. Formatting is the same as in Fig. 3, with waveforms for trials with old words (solid trace) versus trials with new words (dotted trace).

To examine the hypothesis that the left-frontal repetition effect would be found, replicating the chief ERP finding from Experiment 1, mean amplitudes from the same left-frontal electrode cluster were measured over 100-ms intervals from 400 to 900 ms. Significant differences were found for old versus new words at 600–700 ms [$F(1,15)=4.71$, $p<0.05$] and at 700–800 ms [$F(1,15)=5.37$, $p<0.05$]. Differences were nonsignificant for the other 100-ms intervals ($ps>0.05$).

Experiment 2 provided confirmation that subliminally presented exemplars produced two types of repetition effect—a behavioral repetition effect in the form of slowed category-verification responses and an ERP repetition effect in the form of left-frontal ERP negativities for old compared to new words. Moreover, because the relevant categories were not shown in the study phase, the results cannot be attributed to study-phase processing cued by seeing the corresponding category. Fig. 5 shows the scalp topography of ERP repetition effects in the two experiments.

2.2.4. Study-phase ERPs

We analyzed ERPs elicited by the final word or nonword in each study-phase trial (i.e., the 6th presentation). Fig. 6 shows the resulting contrast for 20-ms subliminal words, 20-ms subliminal nonwords, and 80-ms supraliminal words. For this analysis, data were combined across the two experiments. We computed mean amplitudes for these conditions over two intervals (200–400 ms and 400–600 ms) at midline frontal, central, and parietal scalp regions. ERPs after 600 ms were influenced by stimuli for the category-matching test. ERPs obtained from these scalp regions showed very similar amplitudes for 20-ms words and 20-ms nonwords [$ts(15)<1.42$, $ps>0.1$]. ERP amplitudes in these two conditions were smaller than those for 80-ms words, both at 200–400 ms and at 400–600 ms [$ts(15)>5.87$, $ps<0.001$]. We suggest that these ERP differences reflected neural activity associated with conscious word processing, consistent with more extensive analyses conducted by Del Cul et al. (2007). In addition, the similar ERPs yielded by subliminal presentation of words and nonwords may reflect largely comparable perceptual inputs from these presentations that do not evoke conscious perception of the letter strings.

3. General discussion

We characterized neural substrates of conceptual implicit memory for subliminal words in the absence of explicit

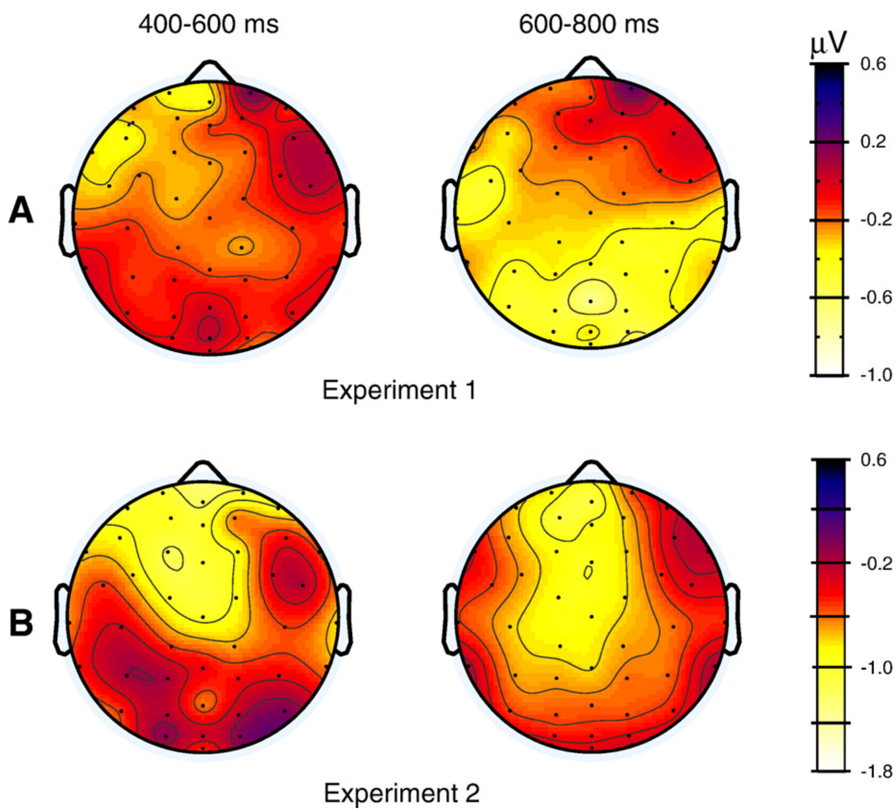

Fig. 5 – Topography of ERP repetition effects collapsed across congruous and incongruous trials. Mean old-minus-new ERP differences were measured for two intervals, 400–600 ms and 600–800 ms intervals. Interpolated topographic maps are shown for (A) Experiment 1 and (B) Experiment 2.

remembering. Because many memory processes co-occur when recognition is tested, special procedures, including subliminal word presentations and cross-modal word repetition, were implemented to diminish the influence of explicit memory and perceptual implicit memory so as to isolate effects related to conceptual implicit memory.

Neural correlates of conceptual implicit memory for subliminal visual words observed here took the form of negative brain potentials over left-frontal scalp locations at 500–800 ms. These potentials were observed in two separate experiments in test conditions wherein spoken exemplars and congruous category words were presented simultaneously. Our findings confirm the notion that ERP effects of repetition of subliminal words can have reasonable durability on the order of minutes, as previously observed by Gaillard et al. (2007), although in that study ERPs were elicited by visual words presented subliminally both times with an intervening delay ranging from 5 s to 47 min. The current investigation focused on conceptual implicit memory, rather than perceptual implicit memory, given that cross-modal word repetition was used with subliminal visual words in the study phase and supraliminal auditory words in the test phase. Unlike Gaillard et al. (2007), we also obtained behavioral evidence of repetition effects for the same trials with ERP repetition effects, as discussed further below.

The use of the category-matching task in the study phase raised a possible concern in Experiment 1 that the participants might have viewed the three categories and attempted to generate potential exemplars. Processes engaged at that point related to category matching and word generation might have influenced test-phase effects, even though the design was controlled such that systematic differences for old versus new words could not arise unless subliminal word information was specifically processed (i.e., an equal number of old and new words in the category-verification test came from each category, and words were counterbalanced across the old and new conditions). In Experiment 2, categories shown at study never matched the subliminal words, but similar behavioral and ERP repetition effects still emerged at test. Therefore, we conclude that repetition effects directly resulted from the subliminal word presentations.

Conscious perception of the masked words presented for 20 ms during the study phase was minimal, as evidenced by three aspects of participants' study-phase performance: (1) they failed to report the subliminal word on over 99% of the trials, (2) they did not discriminate between words and nonwords at greater than chance levels, and (3) they did not select the correct category more often than would be expected by chance. It is still reasonable to question whether participants had some weak conscious perception for subliminal words, perhaps for some proportion of the many trials when they declined to report a word. Although this possibility cannot be excluded, results from objective task performance weigh against it. If subliminal words were consciously perceived but merely not reported, participants should have been able to use this information during the study phase in the

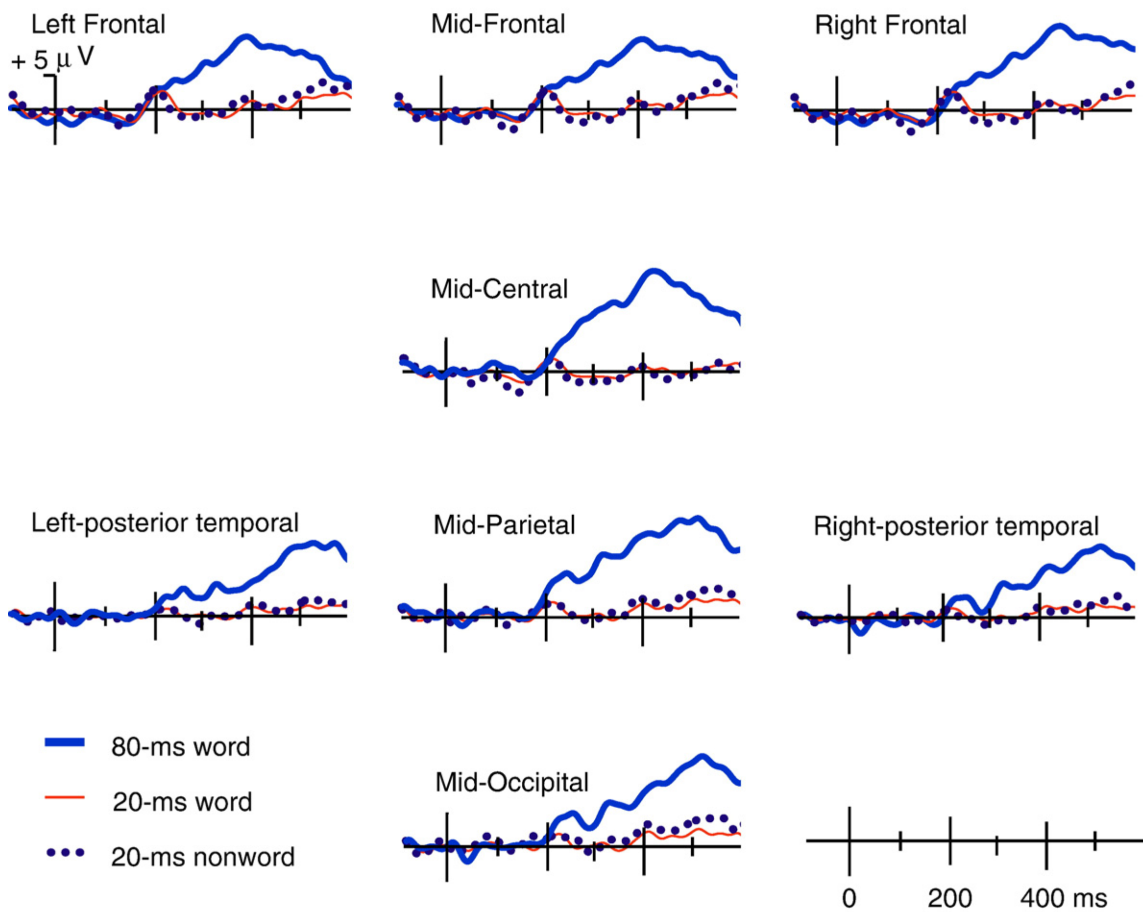

Fig. 6 – Study-phase ERPs for 20-ms word presentations, 80-ms word presentations, and 20-ms nonword presentations. ERPs for 80-ms words deviated from ERPs in the other two study-phase conditions beginning at approximately 200 ms. Waveforms were collapsed across Experiment 1 and Experiment 2 and averaged across groups of electrodes comprising eight scalp regions (as in Figs. 3 and 4).

lexical-decision task (in both experiments) and in the category-matching task (in Experiment 1). And yet, mean scores on these tests were never above chance levels. One might wonder whether participants allocated sufficient attention or effort to performing the tasks, but reasonable accuracy for trials with 80-ms words showed that participants were conscientiously attempting to identify masked words. In short, several lines of evidence suggest that 20-ms words presented during the study phase were unconsciously perceived, which then leads to the further inference that the repetition effects observed in the test phase were not due to conscious memory for those words. That is, if word perception in the study phase was only subliminal and remained only subliminal, then explicit recognition of a word from the study phase would not be possible.

Additional electrophysiological evidence for this same conclusion comes from the ERP effects in the test phase. If the repetition manipulation was contaminated by a subtle contribution from explicit memory, then ERPs to old words would be expected to show reduced versions of effects observed for explicitly remembered words. Based on the literature on ERPs associated with explicit memory (Friedman and Johnson, 2000; Voss and Paller, 2008), we can conclude that the ERP results do not resemble late positive potentials that would be expected for weak levels of memory retrieval on an explicit memory test. Rather, ERPs showed a pattern of brain activity qualitatively different (even opposite in polarity) from ERPs typically associated with conscious memory.

Given the assumption that the processes that give rise to implicit memory often occur during explicit memory tests (Paller et al., 2007), it might be reasonable to expect that ERP old–new contrasts in an explicit memory test would include both ERP correlates of explicit memory and ERP correlates of implicit memory. Yet, the left-frontal old–new ERP effect described here is not typically found in recognition paradigms. Several possible explanations for this can be considered. First, left-frontal ERP negativities may be produced in explicit memory tests but may usually be too small to be reliably observed. Or, they may typically be outweighed by ERP positivities associated with explicit memory processes. Alternatively, the left-frontal ERP negativities may be produced following subliminal learning but not during the usual circumstances of supraliminal learning.

Another way to make sense of these results involves the possibility that some aspect of strategic word processing is influenced by differential conceptual fluency for repeated words. In particular, Schacter et al. (2007) suggested that priming effects may arise from facilitated strategic processing in left-prefrontal cortex. In keeping with these ideas, subliminal visual presentations in our experiments may influence subsequent conceptual processing of spoken words, which may then delay stimulus-to-decision mapping. This alteration in stimulus-to-decision mapping may be reflected by the left-prefrontal ERP effects we observed. If this is the case, then the left-prefrontal effects may reflect changes dependent on response requirements and may not occur in all recognition paradigms. However, we did not obtain evidence for experience-based processing efficiency, whereas Schacter and colleagues proposed that with repetition, "prefrontal regions might become more synchronized with other regions, enabling efficient processing that reflects a tighter coupling between the stimulus and decision."

Conceptual implicit memory with subliminal presentations in the present study took the form of slowed responses in the test-phase category-verification test, rather than speeded responses or an improvement in accuracy. In previous studies of conceptual implicit memory that used supraliminal instead of subliminal presentation, implicit memory effects emerged as an increase in category-cued generation of old words and as response speeding for old words compared to new words in a category-verification test (Vaidya et al., 1997; Gabrieli et al., 1999). In a study with supraliminal face stimuli and famous/nonfamous judgments, conceptual implicit memory for famous faces comprised faster and more accurate behavioral responses (Voss and Paller, 2006). Though at odds with these previous findings based on supraliminal presentation, our results coincide with results from one study using subliminal presentation at study that also led to interference at test (Degonda et al., 2005); following presentation of subliminal face-profession pairings, accuracy of subsequent explicit learning of the same face-profession associations declined. In a related study, reaction-time differences were found in a profession-categorization task when comparing correct and incorrect trials following subliminal face-profession pairings, but responses were not faster following priming from subliminal face-profession pairings, in which conceptual information was embedded, compared to following subliminal faces alone (Henke et al., 2003). Taking all these results together, it is conceivable that subliminal priming leads to additional or qualitatively distinct repetition effects compared to supraliminal priming, and that subliminal presentation may tend to produce response interference in some paradigms, as demonstrated here. Further investigation is needed to understand the underlying mechanisms of such effects.

We have emphasized conceptual processing here due to our use of cross-modal repetition. However, psycholinguistics research distinguishes not just perceptual word processing and conceptual word processing, but also other levels such as a lexical level with no conceptual context. Repetition from the study phase to the test phase in our experiments could include alterations in lexical access. However, we have emphasized the notion of conceptual repetition simply by suggesting that memory processing for repeated words was not based on altered processing of visual representations. Admittedly, we have not determined the precise locus of the repetition effects. As mentioned above, an intriguing notion is that left-prefrontal strategic processing is operative (Schacter et al., 2007). More generally, the repetition effects may concern differential processing of abstract lexical units, of word meanings, of semantic associations based on word meaning, or of a combination of these and other factors. Thus, we emphasize a first-order distinction of processing by attempting to distinguish repetition that can be attributed to repeated processing of the same sensory input (perceptual) from repetition that goes beyond the information inherent in the physical features of the stimulus (conceptual).

Previous fMRI findings have demonstrated reduced left-prefrontal activations for conceptual re-processing of repeated items (Demb et al., 1995; Donaldson et al., 2001; Schacter and Buckner, 1998; Thompson-Schill et al., 1997; Voss et al., 2008), which perhaps reflects the same sort of processing responsible for the current findings of left anterior negativities. Left-frontal ERPs possibly associated with semantic retrieval were also observed by Friedman and Johnson (2000). Although many differences in the paradigms preclude direct comparisons across experiments, the superior temporal resolution of ERPs may provide complementary information on the rapid sequence of neural events responsible for the memory phenomena observed using fMRI. Here, the category-verification test engaged semantic knowledge of test words in a way that was apparently influenced by prior word processing, leading to the left-frontal ERP effects.

In an experiment on brain potentials and congruity with category-exemplar word repetitions, Olichney et al. (2000) found reduced N400 amplitudes for repetitions of incongruous words in a group of patients with amnesia and a group of healthy age-matched individuals. The authors suggested that these ERP effects "*may be the neural correlates of conceptual priming effects*" (p. 1960). Given that altered N400 effects potentially include a contribution from conceptual priming processes (Kutas et al., 2006), similar conceptual processing may be operative in association with ERP effects in the present experiment. However, our study is methodologically unlike most N400 experiments, given the extremely low visibility of study stimuli and the cross-modal word repetition. The divergence in polarity between the present ERP effects (more negative for old words compared to new words) and typical N400-like old–new effects (more positive for old words compared to new words) might also be related to the fact that behavioral results in the present experiment cannot easily be ascribed to facilitated processing of old words. Rather, responses were slower for these words. Further studies are needed to determine whether there is any connection between the polarity of these ERP old–new effects and the facilitation or inhibition shown by behavioral priming effects.

4. Conclusions

The extent to which conceptual implicit memory occurs following subliminal word presentations has not been examined extensively. Furthermore, prior electrophysiological studies of memory for words have faced limitations in convincingly disentangling brain potentials reflecting explicit recognition memory from brain potentials reflecting conceptual implicit memory (Paller et al., 2007). We developed an experimental design with subliminal visual words at study so that we could measure neural correlates of conceptual implicit memory in the absence of conscious remembering. The influence of perceptual implicit memory was reduced by using cross-modal repetition. Neural correlates of conceptual implicit memory for auditory words presented together with visual category labels were distinct from neural correlates of explicit memory observed previously, in keeping with dissociations between explicit memory and implicit memory in amnesic patients (e.g., Gabrieli et al., 1997; Graf et al., 1985; Levy et al., 2004). This evidence of distinct neural correlates for conceptual implicit memory and explicit memory thus substantiates the fundamental differences between these two memory functions and provides a foundation for further investigations of possible relationships or interactions between them.

5. Experimental procedures

5.1. *Participants*

Sixteen different right-handed native English speakers between 18 and 30 years old participated and received monetary compensation in each of two experiments. Each group included ten females and six males. The experimental procedures were explained to all participants and written consent was obtained.

5.2. *Stimuli and design*

Identical stimuli were used in Experiments 1 and 2. Eight exemplars in each of 30 categories (see Appendix) were selected from word norms (Battig and Montague, 1969). Highly typical exemplars (i.e., the first eight ranked exemplars) were not included. Mean typicality rank was 19.3 (SD=8.0), mean word frequency 7.1 per million (SD=8.8), and mean word length 5.8 letters (SD=1.2). These words were spoken by a female native English speaker and comprised a mean duration of 677 ms (SE=99). Fifty other words of the same general type were selected from ten other categories for practice trials (10 words) and 80-ms trials (40 words). Sixty consonant strings were used as nonword stimuli. All study words and nonwords were 4–8 letters in length.

The experiment included 20 blocks, each with a study phase and a test phase. For each study phase, three categories were selected. Each category was used in two blocks, one in the first half and one in the second, and always appearing in the same group of three categories. The sequence of category groups was the same in both halves. A study phase included six 20-ms word trials (two words from each of three chosen categories), three 20-ms nonword trials, and two 80-ms word trials. In the corresponding test phase, the six exemplars (*old words*) and six new exemplars (*new words*, two from each of the same three categories) were presented one at a time, along with one of the three category names. Half of the words at test were paired with congruous category names and the other half with incongruous ones. The groups of old and new words were counterbalanced across participants and were matched for mean typicality, word frequency, and length. Each old and new word appeared in only one block in the experiment.

5.3. *Procedure*

Visual events were presented in white font against a black background on a CRT monitor (100-Hz refresh rate). Participants were asked to use their index, middle, and ring fingers of the right hand to press three corresponding buttons to register responses.

In Experiment 1, as shown in Fig. 1, each study phase started with three category names for 3 s. Eleven trials in a pseudo-random sequence followed, including six 20-ms word trials, three 20-ms nonword trials, and two 80-ms word trials. The presentation sequence in each trial included a fixation cross, a word or nonword, and a mask, all repeated six times in quick succession. For 80-ms trials, the sixth presentation of the word lasted 80 ms instead of 20 ms. These trials were included so that participants would occasionally succeed in perceiving the word, with the assumption that participants would thus maintain their focus on attempting to see each word, which might not happen if they always failed to see the flashed words. The 80-ms words came from categories never used for subliminal words.

Three category names appeared 500 ms after the offset of the last mask. Participants designated one category with a button-press response in an attempt to select the one corresponding to the masked word. Participants were required to guess on every trial and to respond only after the offset of category names (2500 ms after onset). No category matching was included on 80-ms trials, given that these filler words did not fall into any of the categories.

Next, participants decided whether the masked stimulus was a word or a nonword in response to the cue (word or nonword?) that appeared 150 ms after the category designation and disappeared when the response was registered. This procedure served to provide information on the extent to which participants could extract information from the subliminal presentations. Furthermore, at the end of each trial, participants were asked to report any perceived word and were encouraged to guess if they had any clue.

Identical stimuli and study-test procedures were used in Experiment 2, except for two changes at study. First, in each study trial, six different masks were used for each rapid presentation of a study item (e.g., &E#&K&##E&, K#&&EK#E&#, and so on) to further limit conscious perception. Second, the category names presented in the study phase consisted of three categories that did not match any of the words presented in that particular block, and the corresponding category names were used in two other blocks and not within five blocks from when the words from that category appeared. Thus, categories were not repeated from study to test in the same block. Debriefing results showed that participants did not note this mismatching as they were virtually unable to identify masked exemplars.

Approximately 10 s after the study phase, 12 trials of the category-verification test were administered. Each trial included one of the three category names corresponding to words from the prior study phase. In Experiment 1, test-phase categories were the same as those used in the study phase; in Experiment 2, the test-phase categories had not been used in the corresponding study phase. The category name appeared on the screen for 300 ms. Onset of the category name was simultaneous with onset of an auditory word. Half of these words were from the study phase (*old words*) and the other half were not (*new words*). For both old and new words, half were paired with a congruous category (e.g., *BIRD-oriole*) and half with an incongruous category (e.g., *VEHICLE-beets*). To minimize variability in the retention interval across old words, trials were pseudo-randomly intermixed so that old words occurred in the same order as in the study phase. The average retention delay from study-phase word presentation to corresponding old word presentation was thus about 100 s. Participants were asked to respond as rapidly and correctly as possible according to whether the auditory exemplar fit into the visual category by pressing one of two buttons. Half of the participants used the right index finger for 'congruous' and the right middle finger for 'incongruous'; the remaining participants responded in the reverse way. A short rest period was given between blocks.

The duration for the presentation of subliminal words and nonwords was set to last two monitor refresh cycles (i.e., 20 ms at a 100-Hz refresh rate). Stimulus duration was confirmed using an oscilloscope. This combination of display refresh rate and stimulus duration thus provided precise and consistent timing accuracy (as also used by Li et al., 2007b, 2008). The software used for stimulus presentation and response acquisition (Presentation, Neurobehavioral Systems, Inc., Albany, CA) produced experimental logs that were consistent with oscilloscope measurements and were used to verify the consistent timing of stimulus presentation.

EEG was recorded from 59 scalp electrodes, with four electroocular electrodes (two at the external canthi and two infraorbital), all referenced to the right mastoid. Impedance was reduced to below 5 KΩ. The scalp electrodes embedded in an elastic cap (as in Woldorff et al., 2002) were as follows: Fza, Fzp, Fp1m, Fp2m, F3a, F4a, F3s, F4s, FC1, FC2, F7a, F8a, F7p, F8p, F3i, F4i, Cza, Cz, C1a, C2a, C1p, C2p, C3′, C4′, C3a, C4a, C5a, C6a, C5p, C6p, P1′, P2′, PA1a, PA2a, P3i, P4i, P3a, P4a, Pzi, Pzs, PO1, PO2, O1i, O2i, O1′, O2′, Inz, Ozi, Ozs, I1, I2, TI1, TI2, T3′, T4′, TO1, TO2, T35i, T46i [letters denote a location that is anterior (a), posterior (p), inferior (i), superior (s), medial (m), or nearby (′) to the corresponding 10–20 system location]. Biosignals were amplified with a 0.1- to 100-Hz band pass and sampled at a rate of 500 Hz. ERPs were computed for 1000-ms epochs beginning 200 ms prior to stimulus onset. Scalp recordings were re-referenced offline to the average of left and right mastoid recordings. Trials on which baseline-to-peak amplitudes exceeded 120 μV for electroocular electrodes or 70 μV for EEG electrodes were excluded from analyses (11.7% in Experiment 1 and 16.7% in Experiment 2).

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Appendix. Category lists

Document	Body part	Tool	Chemical	Insect
Brochure	Wrist	Drill	Calcium	Locust
Essay	Nail	Screw	Zinc	Flea
Leaflet	Elbow	Vise	Copper	Moth
Journal	Pancreas	Pliers	Lithium	Cricket
Booklet	Abdomen	Ruler	Neon	Tick
Fiction	Lung	Bolts	Chloride	Wasp
Digest	Kidney	Wrench	Mercury	Ladybug
Bulletin	Ankle	Chisel	Sulfur	Termite
Animal	**Fruit**	**Flavoring**	**Asia**	**Girl**
Mule	Lime	Spice	Mongolia	Jean
Camel	Coconut	Vinegar	Nepal	Alice
Raccoon	Lemon	Ketchup	Korea	Helen
Deer	Melon	Ginger	Vietnam	Elaine
Zebra	Avocado	Nutmeg	Taiwan	Margaret
Donkey	Berry	Chives	Malaysia	Nancy
Squirrel	Prune	Mustard	Tibet	Joyce
Wolf	Apricot	Parsley	Cambodia	Donna
Building	**Weapon**	**Occupation**	**Music**	**Boy**
Mall	Shotgun	Nurse	Waltz	Karl
Museum	Spear	Laborer	Concert	Tony
Temple	Dagger	Chemist	Concerto	Steve
Cabin	Pistol	Farmer	Sonata	Bruce
Garage	Bayonet	Banker	Baroque	Terry
Tower	Revolver	Plumber	Swing	Ralph
Mosque	Arrow	Merchant	Song	Peter
Factory	Cannon	Janitor	Ballad	Michael
Color	**Africa**	**Sport**	**Bird**	**Disease**
Violet	Algeria	Skiing	Oriole	Leukemia
Pink	Sudan	Sailing	Swallow	Polio
Magenta	Egypt	Archery	Parrot	Malaria
Beige	Ghana	Polo	Dove	Leprosy
Gray	Albania	Hockey	Falcon	Virus
Maroon	Morocco	Fencing	Hawk	Diabetes
Lavender	Nigeria	Racing	Vulture	Smallpox
Indigo	Kenya	Wrestling	Pigeon	Typhoid
Utensil	**Instrument**	**Weather**	**Vehicle**	**Tree**
Mixer	Harp	Drought	Taxi	Beech
Bowl	Fiddle	Blizzard	Jeep	Hickory
Toaster	Horn	Gale	Trolley	Cedar
Oven	Banjo	Cloudy	Tractor	Willow
Ladle	Tuba	Thunder	Trailer	Cypress

(*continued on next page*)

Appendix (*continued*)

Utensil	Instrument	Weather	Vehicle	Tree
Skillet	Viola	Monsoon	Carriage	Ginkgo
Dish	Cello	Sunny	Wagon	Redwood
Plate	Bass	Humid	Cart	Walnut

Furniture	Crime	Clothing	Vegetable	Boat
Mirror	Homicide	Scarf	Radish	Raft
Stereo	Kidnap	Vest	Kale	Steamer
Rocker	Fraud	Gloves	Turnip	Yacht
Buffet	Treason	Jacket	Cabbage	Barge
Lounge	Felony	Slacks	Beets	Ferry
Bureau	Adultery	Belt	Celery	Canoe
Bench	Forgery	Sweater	Broccoli	Tanker
Cabinet	Perjury	Girdle	Spinach	Clipper

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