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On the Nonautomaticity of Visual Word Processing: Electrophysiological Evidence That Word Processing Requires Central Attention

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The present study used event-related potentials (ERPs) to determine the degree to which people can process words while devoting central attention to another task. Experiments 1–4 measured the N400 effect, which is sensitive to the degree of mismatch between a word and the current semantic context. Experiment 5 measured the P3 difference between low- and high-frequency words. Because these effects can occur only if a word has been identified, both ERP components index word processing. The authors found that the N400 effect (Experiments 1, 3, and 4) and the P3 difference (Experiment 5) were strongly attenuated for Task 2 words presented nearly simultaneously with Task 1. No such attenuation was found when the Task 1 stimulus was presented but required no response (Experiment 2). Strong attenuation was also evident when the Task 2 word was presented before the Task 1 stimulus (Experiment 4), suggesting that central resources are not allocated to stimuli first-come, first-served but rather are strategically locked to Task 1. The authors conclude that visual word processing is not fully automatic but rather requires access to limited central attentional resources.

Keywords: visual word processing, N400 effect, P3, central attention, dual-task performance

Because word reading is an important everyday activity, numerous attempts have been made to understand the underlying processing mechanisms. One specific question of interest is whether humans' cognitive systems can process words in the absence of the central attentional resources needed for carrying out many higher cognitive functions, such as response selection and decision making (e.g., Johnston, McCann, & Remington, 1995; Pashler, 1984). A real-life example would be a driver who is trying to read an important road sign while his or her central attention is engaged with some other task, such as a cell phone conversation.

Single-task studies have provided compelling evidence for the automaticity of word reading. One example is the well-known Stroop effect, where response time (RT) is longer in naming the ink color of a word that spells an incongruent color name than a congruent color name (e.g., the word *RED* printed in green vs. the word *RED* printed in red; see MacLeod, 1991, for a review). This finding suggests that word reading is automatic in the sense that people have great difficulty voluntarily suppressing the reading of a completely irrelevant word (see Besner & Stolz, 1999a, 1999b, for apparent exceptions to this rule).

Dual-task studies, however, have reached divergent conclusions regarding the automaticity of visual word processing. Some have concluded that certain word processes cannot take place while central attention is devoted to another task (e.g., McCann, Remington, & Van Selst, 2000), whereas other studies have reached the opposite conclusion (e.g., Cleland, Gaskell, Quinlan, & Tamminen, 2006). The present study addressed this issue using electrophysiological measures, which can provide more direct indicators of word processing. Before discussing the details of our approach, we first review the most widely used dual-task paradigm and previous studies using this paradigm to study word processing.

The Psychological Refractory Period Paradigm

One approach used to study whether a particular mental process requires central attention is to determine whether this process can proceed in parallel with another task. Researchers adopting this approach have often used the *psychological refractory period* (PRP) paradigm, in which participants are required to perform two speeded tasks on each trial. The critical manipulation is the time interval between these two tasks' onsets, called the stimulus onset asynchrony (SOA). At long SOAs, the two tasks are performed more or less independently, whereas at short SOAs the two tasks demand attentional resources at nearly the same time. A typical finding is that response time for Task 1 (RT1) is roughly constant across SOAs but response time for Task 2 (RT2) increases sharply

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as the SOA decreases, a phenomenon known as the PRP effect (Telford, 1931).

A large body of evidence supports the view that the PRP effect occurs largely because the central stages (e.g., decision making and response selection) for Task 1 and Task 2 do not operate in parallel (for reviews, see Lien & Proctor, 2002; Lien, Ruthruff, & Johnston, 2006; Pashler, 1994; Pashler & Johnston, 1989; see also Meyer & Kieras, 1997, for discussion of the hypothesis that the central bottleneck is strategic rather than structural). This central bottleneck, shown in Figure 1, has been reported to occur even with exceptionally easy tasks and even when tasks have no apparent input conflicts and/or output conflicts (e.g., Lien, McCann, Ruthruff, & Proctor, 2005; Lien, Proctor, & Allen, 2002). In this article, we refer to the limited resource underlying the central bottleneck as *central attention*. Because Task 2 central operations are postponed until Task 1 central operations are completed at short SOAs, this central bottleneck creates a period of cognitive "slack" between the perceptual and central stages of Task 2 (represented by the dotted line in Figure 1).

The Use of the PRP Paradigm to Study Visual Word Processing

Several attempts have been made to use the PRP paradigm to examine whether visual word processing requires central attention (e.g., Allen et al., 2002; Cleland et al., 2006; Lien, Allen, et al., 2006; McCann et al., 2000). In these studies, Task 2 was usually a lexical decision task, in which participants decide whether a letter string is a word or nonword. The key manipulation was whether the words had a low or high frequency of use in the English language (according to norms published by Kučera & Francis, 1967). Participants usually respond more quickly to high-frequency words (e.g., *take*) than to low-frequency words (e.g., *trim*), a phenomenon known as the word frequency effect. Although there is some disagreement regarding the precise locus of word frequency effects, several studies have provided evidence that word frequency effects have primarily a lexical activation locus (e.g., Allen, Smith, Lien, Grabbe, & Murphy, 2005; Monsell, Doyle, & Haggard, 1989). Therefore, it is reasonable to use word frequency effects as a measure of word processing even though word frequency may not be a completely pure measure of lexical access (see, e.g., Balota & Chumbley, 1984; McCann & Besner, 1987).[1]

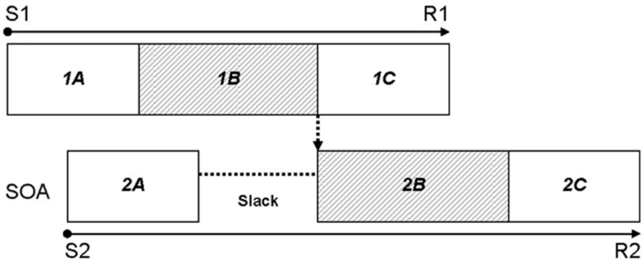

Figure 1. The temporal relations between processing stages of Task 1 and Task 2 at a short stimulus onset asynchrony (SOA) in the psychological refractory period paradigm, as suggested by the central bottleneck model. This model assumes that perceptual and response initiation/execution stages of Task 2 can operate in parallel with any stage of Task 1 but that central stages of Task 2 cannot start until central stages of Task 1 have been completed. 1A, 1B, and 1C are the perceptual, central, and response initiation/execution stages of Task 1, respectively. 2A, 2B, and 2C are the corresponding stages for Task 2. S1 = stimulus for Task 1; S2 = stimulus for Task 2; R1 = response for Task 1; R2 = response for Task 2.

To determine whether Task 2 words can be identified in parallel with Task 1 central processing, researchers have used locus-of-slack logic (see McCann & Johnston, 1992; Pashler, 1984; Schweickert, 1978). According to this logic, if all of the processes leading up to word recognition can proceed without central attention (i.e., are "automatic"), then the word frequency effect on Task 2 should be smaller at short SOAs than at long SOAs (also known as *underadditivity*). The reason is that any lengthening of pre-bottleneck stages of Task 2 (lexical activation, in this case) can be absorbed into the cognitive slack present at short SOAs but not at long SOAs. On the other hand, if word processing requires central attention (i.e., is not "automatic") and therefore cannot proceed in parallel with central operations of another task, then the word frequency effect on Task 2 should be similar at short and long SOAs (also known as *additivity*). Confirming the latter prediction, McCann et al. (2000) found roughly additive effects of word frequency and SOA across several experiments. Accordingly, they concluded that word processing was not completed until after Task 1 central operations were completed, implying that at least some of the processes leading up to lexical activation require central attention.

McCann et al.'s (2000) findings and conclusions are at odds with the widely accepted assumption that word processing is automatic. A recent study by Cleland et al. (2006), however, contradicted McCann et al. Cleland et al. tested a college sample of younger adults, as did McCann et al., but reported a significantly underadditive interaction between word frequency effects and SOA, both when the Task 2 word was visual and when it was auditory. They argued that the statistically additive effect of word frequency and SOA in McCann et al.'s study was due to a lack of statistical power. Whereas the word frequency effect at the long SOA was 127 ms in Experiment 2 (which used a visual word for Task 2) of Cleland et al. (and declined to 70 ms at the short SOA), the effect was only 62 ms in Experiment 1 of McCann et al. (65 ms at the short SOA). Thus, according to Cleland et al., it would have been more difficult for McCann et al. to detect a genuine underadditive interaction. Indeed, McCann et al. did obtain a trend toward underadditivity between the effects of word frequency and SOA in several of their experiments (e.g., Experiments 3 and 4; see their Figures 4 and 5), but it failed to reach statistical significance.

Although Cleland et al. (2006) documented statistically significant underadditivity between the effects of word frequency and SOA, the interaction was weak. Note that the PRP effect was 259 ms, suggesting a long period of cognitive slack, and the word

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[1] Allen et al. (2005) investigated the processing locus of word frequency effects. They first estimated the exposure duration at which individual participants would show chance performance on a lexical decision task. Participants then performed a lexical decision task with exposure durations one screen refresh cycle longer than this estimated value. These brief exposures were used to minimize verification of lexical status (e.g., Paap & Johansen, 1994). Participants continued to show word frequency effects (on both error and A′ measures), suggesting that word frequency affects the early activation stage, not the postword activation stage.

frequency effect at the longest SOA was 127 ms (in Experiment 2). If word processing were fully automatic and word frequency primarily affects lexical activation, then the word frequency effect could have been nearly completely absorbed into the long period of cognitive slack created by the bottleneck. Instead, the percentage of reduction in the word frequency effect on Task 2 at short SOAs was only about 45% (down to 70 ms).

Overall, the results from these studies suggest that some word processes can sometimes proceed without central attention, but are inconclusive (for further discussion, see the *Possible Explanations for Incomplete Attenuation* section in the General Discussion). In addition to producing seemingly inconsistent results across studies, the use of locus-of-slack logic to study word processing has several drawbacks that cloud data interpretation. One complication is the possibility that people can read words in parallel with Task 1 central operations, but when it comes time to perform Task 2 central operations, they restart from scratch (see, e.g., Logan & Gordon, 2001). The logic behind proposing such a restart is that if applied generally (to all activated representations), it would help minimize unwanted carryover from the activated Task 1 representations. Because progress made toward reading the word is lost following the restart, word frequency effects would still occur at short SOAs (thus producing roughly additive effects with SOA). A related possibility is that people can read words in parallel with Task 1 central operations but that these word representations then decay during the bottleneck delay (thought to often last 300 ms or more). Because of this decay, participants would then need to reprocess the word later. These points make it difficult to interpret findings of (approximate) additivity (as in McCann et al., 2000). In such cases, the behavioral measures cannot tell us whether the Task 2 words could not be fully processed without central attention or whether they were in fact fully processed but the progress was subsequently lost (owing to restart or decay). Thus, it is possible that even Cleland et al.'s (2006) results greatly underestimate the true automaticity of visual word recognition. Furthermore, locus-of-slack logic is essentially a variant of additive factors logic, which has been questioned on the grounds that mental processes might operate in cascade rather than in a discrete series (McClelland & Rumelhart, 1981; but see Roberts & Sternberg, 1993).

Findings of partial underadditivity in the PRP paradigm (as in Cleland et al., 2006) are also difficult to interpret definitively. It is logically possible for completely nonautomatic word processing (a bottleneck temporarily preventing all word processes) to nevertheless produce underadditivity. For instance, the lexical access stage might be sped up following the bottleneck delay because processes prior to lexical activation, such as letter identification, provide higher quality input. Even if a slight underadditive interaction is taken as evidence of some automaticity, it is difficult to infer to what degree word processing was able to proceed (e.g., at 50% of the usual rate or only 5%). Furthermore, note that visual word recognition is not a single monolithic process but likely consists of several subprocesses (e.g., visual feature and letter processing, phonological coding, semantic analysis; see Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Mayall, Humphreys, Mechelli, Olsen, & Price, 2001; Reynolds & Besner, 2006). Word frequency effects might tap only relatively early stages of word processing (e.g., lexical activation) and not later stages such as the extraction of meaning (e.g., semantic activation).

We argue that one overriding problem with the previous studies is that overall RT is an indirect indicator of what processes took place along the way toward visual word recognition. These drawbacks suggest a clear need to provide converging evidence using a different approach with a different (and more secure) set of assumptions. To meet this need, the present multiexperiment study assessed the automaticity of visual word processing using event-related potentials (ERPs).

An Electrophysiological Measure of Word Processing

ERPs can provide a continuous measure of brain activity, starting from the moment a stimulus is presented. By examining the time course of ERP components associated with word processing (lexical activation, semantic activation, etc.) in a PRP paradigm, it is possible to determine which components of word processing can occur in parallel with other tasks (i.e., automatically) and which cannot.

One especially useful electrophysiological measure of word processing is the N400, a negative-going brain potential that occurs around 400 ms after the onset of potentially meaningful stimuli (written or spoken stimuli, such as words, pictures, and faces). This component is often called *mismatch negativity* because it occurs most strongly when a stimulus does not match the current context (e.g., Kutas & Hillyard, 1980, 1984). After one sees the word *DOG*, for example, the word *BOOK* (unrelated) would produce mismatch negativity (N400) but the word *POODLE* (related) would not. A critical point is that the N400 provides a definitive indication that a person has actually identified the word and extracted its meaning (see Kutas & Van Petten, 1988, for a review). An absence of the N400, meanwhile, would suggest the nonautomaticity of some stage leading up to the extraction of meaning and the comparison with the current semantic context. For the purpose of indexing the linguistic processing of meaning, the *N400 effect* can be quantified as the average difference in brain potentials between words that are related and unrelated to the current semantic context (Equation 1).

$$\text{N400 effect} = \text{unrelated word ERP} - \text{related word ERP} \quad (1)$$

Electrophysiological measures, such as the N400 effect, often reveal evidence of deeper processing than is apparent in behavioral data (e.g., RT). A study by Vogel, Luck, and Shapiro (1998) provides an excellent example of this point. They studied the attentional blink phenomenon, in which people routinely fail to report the second of two visual targets in a rapid serial visual presentation. Although participants often could not report the identity of the second visual target (a word), that target still produced a robust N400 effect (elicited by the relatedness of the second target with a context word presented earlier). In fact, the amplitude of the N400 effect was just as large at short lags between targets (where the attentional blink occurs) as at much longer lags. These findings suggest that participants identified the visual word stimuli in parallel with the central operations needed for the first target but failed to encode them into memory.

It has been previously claimed that the attentional blink effect and the PRP effect both reflect the same underlying resource limitation: the central bottleneck (e.g., Jolicœur, 1999; Ruthruff &

Pashler, 2001). Therefore, it is natural to suspect that Vogel et al.'s (1998) findings in the attentional blink paradigm would also apply to the PRP paradigm. That is, perhaps participants semantically process visual words in parallel with Task 1 central operations but are unable to maintain those representations during Task 1 central operations. In this case, one would expect the N400 effect to have a similar amplitude and latency at both short and long SOAs.

If, however, some stage leading up to the semantic activation for a word (i.e., the extraction of meaning) requires central attention, it would be hindered by an additional task that is already utilizing limited central resources. Thus, the initial amplitude of the N400 effect elicited by Task 2 words should be reduced at the short SOA relative to the long SOA (i.e., due to fewer attentional resources being allocated to the semantic processing of Task 2). The N400 effect then might be expected to occur later in time (after Task 1 central processing has been completed). In other words, there would be a temporal shift in the latency of the N400 effect. These predictions were tested in the present Experiments 1–4.

To the best of our knowledge, no previous studies have used the N400 effect to study visual word processing in the PRP paradigm. Hohlfeld, Sangals, and Sommer (2004), however, conducted a study on spoken language perception using this approach. In their study, Task 1 was a left–right foot response to the identity of a letter (*L* or *R*) or to the left–right location of a square. Task 2 contained pairs of spoken words: the context word presented prior to Task 1 and the target word presented at an SOA of 100, 400, or 700 ms following Task 1 onset. Participants were to press the left or right key to indicate whether the target word was related or unrelated to the context word. Hohlfeld et al. found that the N400 effect during the time window 300–900 ms post–Stimulus 2 onset was delayed and reduced in amplitude at the 100-ms SOA (Experiment 2). The N400 was not attenuated or delayed, however, when Task 1 required no response (Experiment 1). They concluded that spoken language perception is impeded by the processing of an additional task.

The Present Study

The present study used ERPs to assess to what degree visual word processing occurs while central attention is devoted to another task. In particular, we measured the N400 effect in Experiments 1 - 4 to determine whether the semantic activation for a word requires central attention (as will be described below, Experiment 5 used the P3 difference to examine the automaticity of lexical activation).

Because the N400 effect provides a continuous indicator of semantic activation for a word, it can be used to assess *when* the word was identified and meaning was extracted at different SOAs. If semantic activation requires central attention, then one would expect the N400 effect to have a reduced initial amplitude and a prolonged latency at short SOAs relative to long SOAs. On the other hand, if the processes leading up to semantic activation are not subject to the central bottleneck, and can proceed in parallel with Task-1 central operations, then the N400 effect (both amplitude and latency) elicited by the Task-2 word should be similar at short and long SOAs.

The present study used a PRP paradigm with variable SOA. On each trial, participants performed a tone judgment for Task 1 and a word judgment for Task 2. To elicit an N400, Experiments 1–4 used a semantic relatedness judgment for Task 2 (rather than the lexical decision task used in previous behavioral studies; but see Experiment 5). Specifically, participants judged whether the Task 2 word was related or unrelated to a previously presented context word (see the event timeline shown in Figure 2). It is important to note that our primary focus is the effect of relatedness on ERPs (i.e., the N400 effect), not the effect of relatedness on RT. Whereas

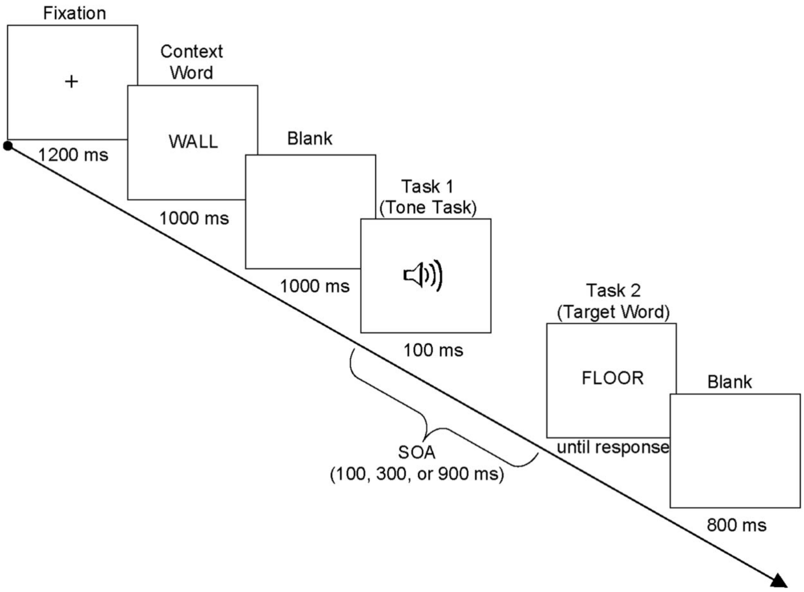

Figure 2. An example event sequence in Experiment 1. In this example, the context word and the Task 2 target word were related. In the real experiment, the context word was printed in blue and the Task 2 target word was printed in white, against a black background. SOA = stimulus onset asynchrony.

word frequency effects on RT can be meaningfully interpreted using locus-of-slack logic (as in previous behavioral studies and in the present Experiment 5), the same is not true for the relatedness effect. The semantic relatedness manipulation (unlike word frequency) is not intended to make word processing take more or less time. Furthermore, if there is an effect of relatedness on RT, we would not know exactly which processing stages were influenced. Note that related and unrelated responses are made with different fingers, and so any relatedness effect on RT might simply reflect a modulation of response processes.

Looking ahead to the results, Experiment 1 revealed that a normal N400 effect was evident at the 900-ms SOA but was strongly attenuated at the 100-ms SOA. Experiment 2 demonstrated that this effect is specifically due to central operations engaged by Task 1, not the mere presence of the Task 1 stimulus. Experiment 3 replicated this effect using a slightly different paradigm that made it easier for participants to hold the context word in memory. Experiment 4 tested whether the attenuation of the N400 effect to Task 2 at short SOAs is due specifically to competition between Task 1 and Task 2 for access to central resources. Finally, to provide converging evidence and to narrow down the locus of the processing limitation, Experiment 5 used a different ERP component (namely, the P3) thought to specifically index lexical activation.

Experiment 1

Experiment 1 used the N400 effect to test whether semantic activation for a word is automatic—in other words, whether the meaning of the Task 2 word can be extracted while central attention is devoted to Task 1. To minimize possible input and output conflicts between Task 1 and Task 2, we used nonlinguistic auditory stimuli and foot responses for Task 1 and used visual words and keypress responses for Task 2. On each trial, participants first viewed a context word (see Figure 2), which needed to be remembered but did not require any response. Next the Task 1 tone was presented. After a variable SOA, the Task 2 stimulus arrived. Participants were to indicate whether this word was related or unrelated to the context word.

Method

Participants. Twelve undergraduate students from Oregon State University participated in exchange for extra course credit. Their mean age was 21 years, with a range of 19 to 24 years. They were all native English speakers and had normal or corrected-to-normal vision.

Apparatus and stimuli. Stimuli were presented on an IBM-compatible microcomputer connected to a 19-in. ViewSonic monitor, an E-prime response box, and customized foot pedals. The Task 1 stimulus was a pure tone or white noise (similar to a hissing sound). The context word was printed in blue and the Task 2 word was printed in white, against a black background, in the center of the screen (see Figure 2). The words were presented entirely in uppercase letters in an Arial 18-point font. Each letter was approximately 0.8 cm in width and 0.9 cm in height. At a typical viewing distance of 55 cm, each letter subtended a visual angle of 0.83° × 0.94°. The Task 2 target word was either semantically related (50% of trials) or unrelated (50% of trials) to the context word. For instance, the target word *FLOOR* was related to the context word *WALL*, whereas the target word *FOOD* was unrelated to the context word *GATE*.

The list of related word pairs was taken from Vogel et al. (1998; Experiment 2).[2] The unrelated word pair was formed by taking the same set of context and target words but paired differently. Thus, each word appeared twice for each participant, once in the related condition and once in the unrelated condition. Six different unrelated word pair lists were randomly generated, with a few repairings to avoid accidental relatedness (which happened about 5% of the time). Each participant was assigned to receive one of these six lists, so that each list was used equally often across participants.

Design and procedure. Each trial started with the plus sign (fixation) in the center of the screen for 1,200 ms, which was then replaced with the context word for 1,000 ms. The Task 1 auditory stimulus appeared 1,000 ms after the offset of the context word and lasted for 100 ms. After one of the three SOAs (100, 300, or 900 ms, intermixed within blocks), the Task 2 target word appeared and remained on the screen center until the participant had responded to both Task 1 and Task 2. The fixation for the next trial appeared 800 ms after the response for the previous trial (see Figure 2).

For Task 1, participants were asked to depress the left pedal (with their left foot) for the pure tone and the right pedal (with their right foot) for the noise sound. For Task 2, participants were asked to press the leftmost response-box button with their left index finger if the Task 2 target word was related to the context word and the rightmost button with their right index finger if the Task 2 target word was unrelated to the context word. They were asked to respond to Task 1 before Task 2 and to respond to both tasks quickly and accurately.

Participants performed two practice blocks of 30 trials each, followed by 12 experimental blocks of 60 trials each. Participants received a summary of mean RT and accuracy at the end of each block. They were encouraged to take a break before beginning the next block. The entire session lasted approximately 2 hr, with the computerized experiment lasting about 70 min.

Electroencephalographic (EEG) activity recording and analyses. The EEG activity was recorded using Q-cap AgCl electrodes from F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, F7, F8, P3, Fc5, Fc6, T7, T8, Cp5, Cp6, P7, P8, O1, and O2. These sites and the right mastoid were recorded in relation to a reference electrode at the left mastoid. The ERP waveforms were then rereferenced offline to the average of the left and right mastoids (see Luck, 2005). The horizontal electrooculogram (HEOG) was recorded bipolarly from electrodes at the outer canthi of both eyes, and vertical electrooculogram (VEOG) was recorded from electrodes above and below the midpoint of the left eye. Electrode impedance was kept below 5 kΩ. EEG, HEOG, and VEOG were amplified using Synamps2 (Neuroscan) with a gain of 2,000 and a bandpass of 0.1–70 Hz. The amplified signals were digitized at 250 Hz.

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[2] We thank Edward Vogel for providing the word lists used in Vogel, Luck, and Shapiro (1998). Starting from this list, we modified a few of the word pairs and formed six different lists of word pairings to be used in the unrelated condition.

Trials with possible ocular and movement artifacts were identified automatically using a threshold of ± 75 μV for a 1,400-ms epoch beginning 200 ms before Task 2 stimulus onset to 1,200 ms after Task 2 stimulus onset. Each of these candidate artifact trials was then inspected manually. This procedure led to the rejection of 17.14% of the trials, with no more than 25% rejected for any individual participant in the final data analyses.

The averaged ERP waveforms were time locked to the onset of the Task 2 target word. Difference waves were constructed by subtracting the ERP waveforms elicited by Task 2 target words related to the context word from the ERP waveforms elicited by Task 2 target words unrelated to the context word (i.e., the N400 effect; see Equation 1), collapsed across the three parietal electrode sites (P3, Pz, and P4).

We conducted two different data analyses on the difference waveforms. The first data analysis was intended to examine whether the N400 effect was attenuated at the short SOAs compared with the long SOAs. In this analysis, we followed Vogel et al. (1998) and measured the mean amplitude of the N400 effect from 300 to 500 ms after Task 2 stimulus onset relative to the 200-ms baseline period before Task 2 stimulus onset. This is the time window during which the N400 effect is typically maximal in single-task conditions (and at long SOAs).

The second data analysis was intended to examine whether the N400 effect was shifted in time at the short SOA relative to the long SOA, as might occur if a bottleneck temporarily prevented word processing. In this analysis, we followed Hansen and Hillyard (1980) and measured the latency of the N400 effect using the fractional area technique (also called the 50% area latency measure; see Luck, 2005, for detailed discussion of the advantages of this measure over other latency measures). The latencies were determined within a broad time window from 200 to 1,200 ms after Task 2 stimulus onset, using the jackknife procedure (Ulrich & Miller, 2001). Analysis of variance (ANOVA) was used for all statistical analyses. The p values were adjusted using the Greenhouse–Geisser epsilon correction for nonsphericity.

Results

In addition to trials with ocular artifacts, trials were excluded from the final analyses of behavioral data (RT and proportion of errors [PE]) and EEG data if RT was less than 100 ms or greater than 2,000 ms (1.32% of trials exceeded these cutoff values). Trials were also excluded from RT and EEG analyses if the response was incorrect.

Behavioral data analyses. The ANOVAs on RT and PE for Task 1 and Task 2 were conducted as a function of Task 2 context–target relatedness (related and unrelated) and SOA (100, 300, and 900 ms). Figure 3 shows mean RT, and Table 1 shows mean PE, for Task 1 and Task 2 in each condition. Although we report the analysis of behavioral data for the sake of completeness, note that our experimental logic rests on the ERP data (the N400 effect), not the behavioral data.

For Task 1, mean RT was 40 ms longer at the shortest SOA than at the other SOAs, $F(2, 22) = 11.67$, $p < .001$, $MSE = 1{,}219$, $\eta_p^2 = .51$; a similar effect was observed for PE, $F(2, 22) = 6.29$, $p < .01$, $MSE = 0.0001$, $\eta_p^2 = .36$. No other effects were statistically significant.

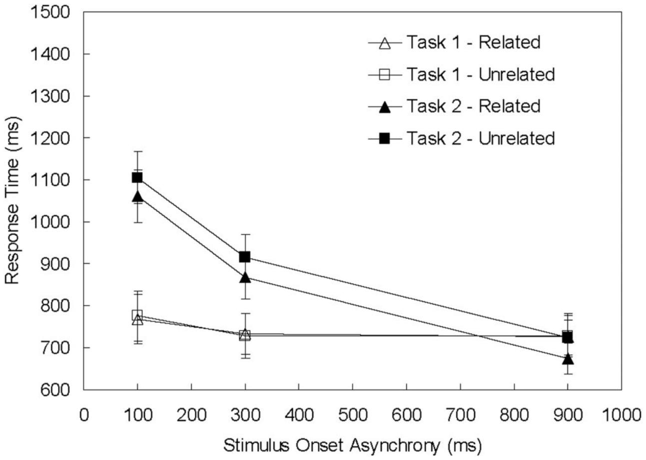

Figure 3. Mean response times for Task 1 and Task 2 in Experiment 1 as a function of Task 2 context–target relatedness (related and unrelated) and stimulus onset asynchrony (100, 300, and 900 ms). Error bars represent the standard error of the mean (based on between-subjects variance in that condition).

For Task 2, RT2 increased as SOA decreased, $F(2, 22) = 108.91$, $p < .0001$, $MSE = 8{,}112$, $\eta_p^2 = .91$, reflecting a 383-ms PRP effect. RT2 was 47 ms longer when the Task 2 target word was unrelated to the context word than when it was related, $F(1, 11) = 19.54$, $p < .001$, $MSE = 2{,}033$, $\eta_p^2 = .64$. This relatedness effect was roughly constant across SOAs, as indicated by the nonsignificant interaction between SOA and Task 2 context–target relatedness ($F < 1.0$); the relatedness effect on RT2 was 44, 48, and 49 ms at the 100-, 300-, and 900-ms SOAs, respectively. No effect was significant in the analyses of PE2.

ERP analyses: Attenuation of the N400 effect. The mean amplitudes of the difference waveforms between unrelated and related words from 300 to 500 ms after the onset of the Task 2 stimulus (when the N400 effect is usually maximal) were analyzed as a function of SOA (100, 300, and 900 ms). The N400 effect was significantly influenced by SOAs, $F(2, 22) = 14.90$, $p < .0001$, $MSE = 3.323$, $\eta_p^2 = .58$. Pairwise comparisons showed that the N400 effect was more negative (i.e., larger) at the 900-ms SOA (–5.689 μV) than at the 300-ms SOA (–2.738 μV), $F(1, 11) = 20.74$, $p < .001$, $MSE = 8.771$, $\eta_p^2 = .65$, and at the 100-ms SOA (–1.796 μV), $F(1, 11) = 46.07$, $p < .0001$, $MSE = 2.269$, $\eta_p^2 = .81$. The N400 effect was not significantly different between the two shorter SOAs (100 ms and 300 ms), $F(1, 11) = 1.20$, $p = .2974$, $MSE = 8.900$, $\eta_p^2 = .10$. In summary, a substantial N400 effect was present at the 900-ms SOA during this time window but was strongly attenuated at the 300-ms and 100-ms SOAs (see Figure 4). This finding is consistent with a reduction in semantic processing of the Task 2 word while Task 1 central operations are still underway.

ERP analyses: A temporal shift of the N400 effect. As noted above, there is a reduction in the N400 effect amplitude at short SOAs during the time period 300–500 ms following the onset of the Task 2 word. If semantic activation triggered by a word is delayed by a central processing bottleneck, the N400 effect amplitude at short SOAs should initially be reduced but then occur later in time (after Task 1 central stages have finished). To look for

Table 1
Proportion of Errors for Task 1 and Task 2 (Standard Error of the Mean in Parentheses) as a Function of Task 2 Context-Target Relatedness and Stimulus Onset Asynchrony in Experiment 1

Task 2 context-target relatedness	Stimulus onset asynchrony		
	100 ms	300 ms	900 ms
	Task 1		
Related	.018 (.003)	.008 (.003)	.010 (.004)
Unrelated	.014 (.005)	.007 (.003)	.006 (.003)
	Task 2		
Related	.088 (.018)	.084 (.018)	.077 (.015)
Unrelated	.063 (.022)	.069 (.021)	.047 (.016)

evidence of such a delay in the N400 effect, we calculated the time it took, at each SOA, for the total N400 effect amplitude (the area under the curve) to reach 50% of its value (i.e., the fractional area technique; see Luck, 2005) during the time window 200–1,200 ms following the onset of the Task 2 word. To determine whether the effects of SOA were significant, we submitted jackknifed latency estimates for the different SOAs to a repeated measures ANOVA; F values were corrected (F_c) according to the formula provided by Ulrich and Miller (2001).

Using this approach, we found that the latency of the N400 effect was significantly different across SOAs, $F_c(2, 22) = 5.80$, $p < .01$; the latency was 635, 503, and 423 ms at the 100-, 300-, and 900-ms SOAs, respectively. Pairwise comparisons revealed that the latency of the N400 effect was significantly longer at the 100-ms SOA than at the 900-ms SOA, $F_c(1, 11) = 15.39$, $p < .01$. The difference in latency between the two shortest SOAs approached significance, $F_c(1, 11) = 4.27$, $.05 < p < .10$. The

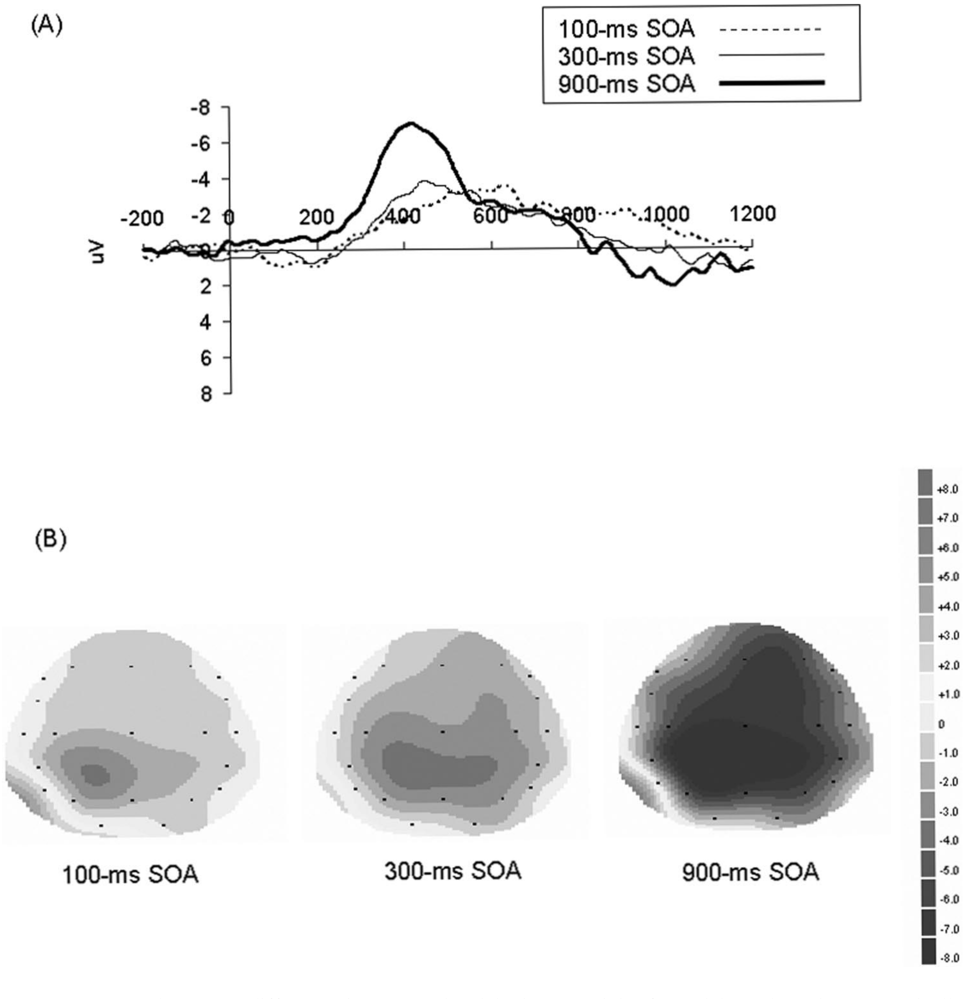

Figure 4. Grand average difference in event-related brain potentials, formed by subtracting semantically related Task 2 trials from semantically unrelated Task 2 trials (i.e., the N400 effect) in Experiment 1. Panel A shows the difference waveforms at the parietal electrode sites (data collapsed across the P3, Pz, and P4 electrodes). Negative is plotted upward and time zero represents Task 2 onset. The baseline period was the 200 ms prior to Task 2 stimulus onset. Panel B shows the scalp topography of the difference waveforms during the time window 300–500 ms after Task 2 word onset for each stimulus onset asynchrony (SOA).

difference in latency between the two longest SOAs was not significant, $F_c(1, 11) = 2.12, p > .05$. In summary, as can be seen in Figure 4, an N400 effect was delayed at the 100-ms SOA compared with the 900-ms SOA, consistent with the hypothesis that semantic processing of the Task 2 word is delayed while Task 1 central operations are still underway.

Discussion

The main purpose of Experiment 1 was to determine whether semantic activation for a word (the extraction of meaning), as indexed by the N400 effect, can proceed while central operations are devoted to another task. The critical finding is that the N400 effect averaged across the parietal sites was markedly reduced (by about 68%) at the 100-ms SOA relative to the 900-ms SOA, during the critical time window (300–500 ms after Task 2 stimulus onset). This finding rules out the restart hypothesis, which asserts that people read words in parallel with Task 1 central operations but restart from scratch when performing Task 2 central operations (see introduction for details; see also, e.g., Logan & Gordon, 2001). Likewise, it also rules out the hypothesis that people read words in parallel with Task 1 central operations but then word representations decay during the bottleneck delay (which might last 300 ms or longer). Our N400 data reveal no evidence of initial success in processing the words.

If semantic activation for a word is delayed by the central bottleneck, the N400 effect should be initially suppressed at short SOAs but then occur later in time (after Task 1 central operations have finished). Consistent with this claim, the latency of the N400 effect was longer at the 100-ms SOA (635 ms) than at the 900-ms SOA (423 ms). It is interesting also to ask whether the delayed N400 effect at short SOAs was just as large in amplitude as the N400 effect obtained at long SOAs. From a casual inspection of Figure 4, it might appear that the amplitude is lower at short SOAs because the peak value is lower. However, a lower peak could simply be due to smearing of the N400 difference (due to extra variance across trials and across participants at the short SOA). To address this issue more carefully, we need to estimate the total amplitude of the N400 effect (i.e., the area under the curve). We chose to focus on the time window 200–1,200 ms after Task 2 word onset, which appears to cover the entire N400 effect, even at short SOAs. The overall average amplitude of the N400 effect was similar at all SOAs (–1.606, –1.109, and –1.581 μV at the 100-, 300-, and 900-ms SOAs, respectively; $F < 1.0$). These results suggest that semantic activation of the Task 2 word was initially blocked and then occurred more or less fully at a later point in time (i.e., after Task 1 central operations were completed).

Experiment 2

We have proposed that the attenuation of the N400 effect at the short SOA relative to the long SOA in Experiment 1 was due to the lack of central attention. An alternative explanation, however, is that the N400 effect to the word was reduced at short SOAs simply because the Task 1 auditory stimulus and the Task 2 target word appeared closely together in time. Because the Task 1 auditory stimulus is always unrelated to the context word, it may diminish the ability of the Task 2 target word to produce mismatch negativity. Although this explanation seems unlikely, it is important to rule it out. To test it, in Experiment 2 we presented the same exact stimuli as in Experiment 1 but without the requirement to actually respond to the Task 1 stimuli. The question is whether the N400 effect elicited by the Task 2 target word would still be attenuated at short SOAs.

If the attenuation of the N400 effect at the short SOAs of Experiment 1 was due simply to the temporal synchrony of the Task 1 and Task 2 stimuli, then it should occur in the present experiment as well. But if this attenuation of the N400 effect was instead due to the lack of central attention, then it should not occur in the present experiment (in which there is no competition between tasks for central attention).

Method

Participants. There were 12 participants, drawn from the same participant pool as in Experiment 1. None had participated in the previous experiment.

Apparatus, stimuli, and procedure. The tasks, stimuli, and equipment were the same as in Experiment 1, except that no response was required to the Task 1 stimulus.

Results

Although there was no Task 1 in this study, we continue referring to the word task as *Task 2* for the sake of continuity. The data analysis was similar to that of Experiment 1 but applied only to Task 2 performance. Application of the RT cutoffs eliminated approximately 2.5% of trials. Rejection of trials with ocular artifacts in the EEG data led to the further elimination of 9.7% of trials but no more than 23% of trials for any individual participant.

Behavioral data analyses. The ANOVAs on RT and PE for Task 2 were conducted as a function of Task 2 context–target relatedness (related and unrelated) and SOA (100, 300, and 900 ms). Table 2 shows mean RT and PE for Task 2 in each condition.

For Task 2, RT2 increased slightly as SOA decreased, $F(2, 22) = 13.08, p < .001, MSE = 753, \eta_p^2 = .54$; RT2 was 710, 695, and 670 ms at the 100-, 300-, and 900-ms SOAs, respectively. Thus, a PRP effect of 40 ms was obtained, which is only about 10% the size of the PRP effect found in Experiment 1. RT2 was also 48 ms shorter with related Task 2 words than with unrelated Task 2 words, $F(1, 11) = 9.10, p < .05, MSE = 4{,}574, \eta_p^2 = .45$.

Table 2
Mean Response Time (in Milliseconds) and Proportion of Errors for Task 2 (Standard Error of the Mean in Parentheses) as a Function of Task 2 Context-Target Relatedness and Stimulus Onset Asynchrony in Experiment 2

Task 2 context-target relatedness	Stimulus onset asynchrony		
	100 ms	300 ms	900 ms
	Response time		
Related	678 (41)	671 (47)	654 (46)
Unrelated	742 (57)	719 (58)	686 (56)
	Proportion of errors		
Related	.092 (.017)	.083 (.014)	.087 (.019)
Unrelated	.031 (.006)	.020 (.007)	.020 (.006)

Although the Task 2 context–target relatedness effect was numerically larger at the short SOA than at the long SOA, the interaction between SOA and Task 2 context–target relatedness was not significant, $F(2, 22) = 2.89$, $p = .0801$, $MSE = 500$, $\eta_p^2 = .21$. The Task 2 relatedness effect was 63, 49, and 32 ms at the 100-, 300-, and 900-ms SOAs, respectively. For PE2, only the main effect of Task 2 context–target relatedness was significant, $F(1, 11) = 19.15$, $p < .01$, $MSE = 0.0038$, $\eta_p^2 = .64$. PE2 was .063 higher when the Task 2 target word was related to the context word than when it was unrelated. No other effect was significant.

ERP analyses: Attenuation of the N400 effect. As in Experiment 1, we conducted two different N400 effect analyses. The first one focused on the mean amplitude of difference waveforms during the 300–500-ms post–Task 2 stimulus onset. As shown in Figure 5, the N400 effect was roughly equally large at all SOAs, $F(2, 22) = 1.78$, $p = .1967$, $MSE = 1.367$, $\eta_p^2 = .14$; the mean amplitude of the N400 effect was –3.203, –3.914, and –4.037 μV at the 100-, 300-, and 900-ms SOAs, respectively. Pairwise comparisons revealed no significant differences between these SOAs, $Fs(1, 11) \leq 3.90$, $ps \geq .07$, $MSEs \leq 3.672$.

ERP analyses: A temporal shift of the N400 effect. The second data analysis aimed to determine whether there was a temporal shift of the N400 effect during the time window 200–1,200 ms following the onset of the Task 2 stimulus. In this analysis, there was no significant effect of SOA on the latency of the N400 effect, $F_c(2, 22) = 1.15$, $p > .05$; the latency was 450, 403, and 434 ms at the 100-, 300-, and 900-ms SOAs, respectively. Pairwise comparison revealed no significant difference between any two SOAs, $F_c s(1, 11) \leq 3.40$, $ps > .05$.

Discussion

The purpose of Experiment 2 was to examine whether the attenuation of the N400 effect at the short SOA in Experiment 1

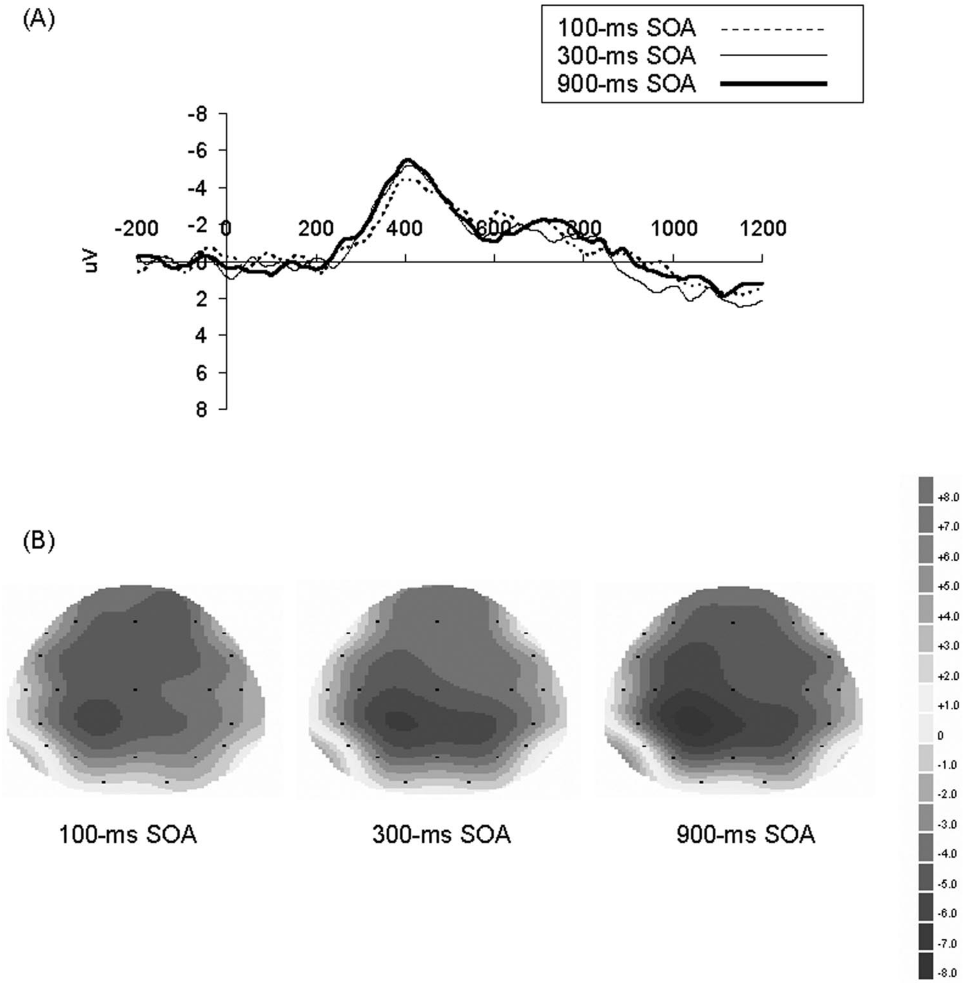

Figure 5. Grand average difference in event-related brain potentials, formed by subtracting semantically related Task 2 trials from semantically unrelated Task 2 trials (i.e., the N400 effect) in Experiment 2. Panel A shows the difference waveforms at the parietal electrode sites (data collapsed across the P3, Pz, and P4 electrodes). Negative is plotted upward and time zero represents Task 2 onset. The baseline period was the 200 ms prior to Task 2 stimulus onset. Panel B shows the scalp topography of the difference waveforms during the time window 300–500 ms after Task 2 word onset for each stimulus onset asynchrony (SOA).

occurred simply because of the temporal proximity of the Task 1 and Task 2 stimuli. Experiment 2 was similar to Experiment 1, except that participants responded to Task 2 only, ignoring the Task 1 stimulus. As shown in Figure 5, the N400 effect elicited by the Task 2 target word was similar in amplitude and latency at all SOAs. Even over the extended time window 200–1,200 ms after Task 2 stimulus onset, the overall average amplitude of the N400 effect was similar across SOAs (−0.992, −0.796, and −1.210 μV at the 100-, 300-, and 900-ms SOAs, respectively; $F < 1.0$). Thus, the attenuation of the N400 effect in response to the Task 2 words at the short SOA in Experiment 1 cannot be attributed simply to temporal synchrony between the stimuli. Instead, the attenuation appears to be due primarily to the lack of central attention. In sum, these results support the hypothesis that the semantic processing of visual words requires central attention.

Experiment 3

Experiment 3 had two main purposes. First, it was a conceptual replication of Experiment 1, investigating the automaticity of visual word recognition under different conditions. Second, it tested an alternative explanation of the Experiment 1 results. Perhaps people can identify words without central attention, but central operations are needed to first retrieve the context word. This hypothesis is plausible because the context word changed on every single trial. To get around this problem, we switched to a categorization task: Participants indicated whether the Task 2 word was related or unrelated to a given category name (see Appendix). This task allowed us to use the same context word (category name) for entire blocks of trials.

As in Experiment 1, participants made a foot response to auditory stimuli for Task 1 and made a keypress response to a word for Task 2. However, instead of presenting a context word prior to each trial, we presented a category name prior to each *block* of trials. The question is whether the N400 effect elicited by the Task 2 target word will still be attenuated at the short SOA, as in Experiment 1.

Method

Participants. There were 12 participants, drawn from the same participant pool as in the previous experiments. None had participated in the previous experiments. All of them were native English speakers and had normal or corrected-to-normal vision. As in Experiments 1 and 2, there were six different versions of the unrelated word lists, counterbalanced across participants.

Apparatus, stimuli, and procedure. The tasks, stimuli, and equipment were the same as in Experiment 1, except for Task 2. Instead of presenting the context word prior to each trial, we presented the category word (e.g., *furniture*) only at the beginning of each block. In a given trial within that block, the Task 2 target word was equally likely to be related or unrelated to that category word (see Appendix for related word lists). Participants were to press the leftmost button for related words and the rightmost button for unrelated words.

Results

The data analysis was similar to that of Experiment 1. Application of the RT cutoffs eliminated 2.47% of trials. Rejection of trials with ocular artifacts in the EEG data led to the further elimination of 13.12% of trials but no more than 25% of trials for any individual participant.

Behavioral data analyses. Figure 6 shows the mean RT and Table 3 shows the mean PE for Task 1 and Task 2 in each condition. For Task 1, Mean RT1 was about 70 ms longer at the shortest SOA than at the other SOAs, $F(2, 22) = 10.69$, $p < .001$, $MSE = 3{,}878$, $\eta_p^2 = .49$. A similar effect was observed for PE1, $F(2, 22) = 9.02$, $p < .01$, $MSE = 0.0002$, $\eta_p^2 = .45$; PE1 was .01 larger at the shortest SOA than at the other SOAs. No other effects were statistically significant.

For Task 2, mean RT2 increased as SOA decreased, $F(2, 22) = 52.91$, $p < .0001$, $MSE = 19{,}404$, $\eta_p^2 = .83$, reflecting a 414-ms PRP effect. Neither the main effect of relatedness, $F(1, 11) = 1.47$, $p = .2511$, $MSE = 2{,}153$, $\eta_p^2 = .12$, nor its interaction with SOA was significant, $F(2, 22) = 1.63$, $p = .2268$, $MSE = 940$, $\eta_p^2 = .13$. The Task 2 relatedness effect was –5, 24, and 21 ms at the 100-, 300-, and 900-ms SOAs, respectively. The relatedness effect was significant on PE2, $F(1, 11) = 31.10$, $p < .001$, $MSE = 0.0012$, $\eta_p^2 = .74$; PE2 was .046 smaller when the Task 2 target word was unrelated to the category word than when it was related. No other effect was significant.

ERP analyses: Attenuation of the N400 effect. The mean amplitude of the N400 effect at the parietal electrode sites during the time window 300–500 ms after Task 2 stimulus onset was influenced by SOA, $F(2, 22) = 3.97$, $p < .05$, $MSE = 2.427$, $\eta_p^2 = .27$. Pairwise comparisons showed that the difference between the 100-ms SOA and the 900-ms SOA was significant, $F(1, 11) = 10.67$, $p < .01$, $MSE = 3.282$, $\eta_p^2 = .49$. The comparison between the 100-ms SOA and the 300-ms SOA approached significance, $F(1, 11) = 4.06$, $p = .0689$, $MSE = 5.194$, $\eta_p^2 = .27$. On the other hand, there was no statistical difference in the N400 effect between the 300-ms SOA and the 900-ms SOA ($F < 1.0$). In summary, as can be seen in Figure 7, the N400 effect was more negative (i.e., larger) at the 900-ms SOA (–3.345 μV) and the 300-ms SOA (–2.963 μV) than at the 100-ms SOA (–1.637 μV). The attenua-

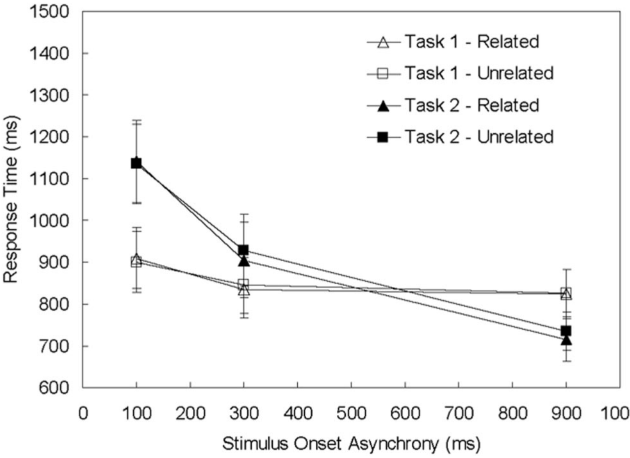

Figure 6. Mean response times for Task 1 and Task 2 in Experiment 3 as a function of Task 2 category–target relatedness (related and unrelated) and stimulus onset asynchrony (100, 300, and 900 ms). Error bars represent the standard error of the mean (based on between-subjects variance in that condition).

tion of the N400 effect at the 100-ms SOA is consistent with a reduction in semantic activation for a word in the absence of central attention.

ERP analyses: A temporal shift of the N400 effect. As in Experiments 1 and 2, we conducted fractional area latency analyses to examine whether there was a temporal shift of the N400 effect during the time window 200–1,200 ms after Task 2 stimulus onset. The resulting latencies were 476, 441, and 314 ms at the 100-, 300-, and 900-ms SOAs, respectively. The overall SOA effect did not reach statistical significance ($F_c < 1.0$), and pairwise comparisons revealed no significant difference between any two SOAs (F_cs < 1.0). Although not statistically significant, there was a substantial trend toward longer latencies at the short SOA than at the long SOA (162 ms), similar in magnitude to that observed in the other N400 experiments reported in this article (where the SOA effect was statistically significant; see Experiments 1 and 4).

Table 3
Proportion of Errors for Task 1 and Task 2 (Standard Error of the Mean in Parentheses) as a Function of Task 2 Category-Target Relatedness and Stimulus Onset Asynchrony in Experiment 3

Task 2 category-target relatedness	Stimulus onset asynchrony		
	100 ms	300 ms	900 ms
	Task 1		
Related	.030 (.007)	.019 (.004)	.018 (.005)
Unrelated	.034 (.010)	.022 (.007)	.018 (.007)
	Task 2		
Related	.079 (.009)	.081 (.014)	.079 (.011)
Unrelated	.032 (.006)	.035 (.009)	.037 (.011)

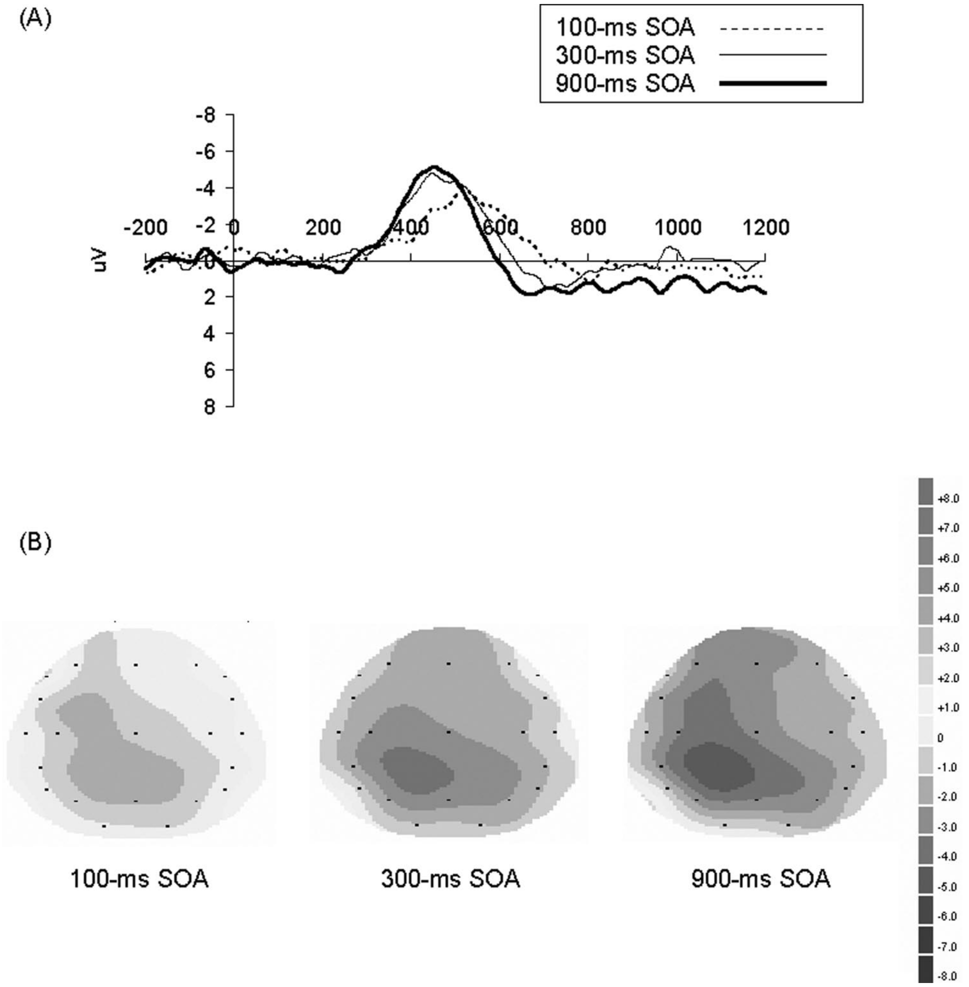

Figure 7. Grand average difference in event-related brain potentials, formed by subtracting category-related Task 2 trials from category-unrelated Task 2 trials (i.e., the N400 effect) in Experiment 3. Panel A shows the difference waveforms at the parietal electrode sites (data collapsed across the P3, Pz, and P4 electrodes). Negative is plotted upward and time zero represents Task 2 onset. The baseline period was the 200 ms prior to Task 2 stimulus onset. Panel B shows the scalp topography of the difference waveforms during the time window 300–500 ms after Task 2 word onset for each stimulus onset asynchrony (SOA).

Discussion

Experiment 3 used a category–target relatedness Task 2 rather than a context–target relatedness Task 2. Because the category name was constant within a block rather than changing trial by trial, it minimized the need to retrieve the category words from memory. Nevertheless, Experiment 3 showed similar results as in Experiment 1. During the time window 300–500 ms after Task 2 word onset (when the N400 effect is usually maximal), the mean amplitude of the N400 effect was reduced by 51% at the 100-ms SOA relative to the 900-ms SOA. This finding, which replicates the results of Experiment 1, suggests that the semantic processing of visual words is strongly attenuated while Task 1 central operations are still underway.

There was a trend, although not significant, for an increase in N400 latency at the short SOA compared with the long SOA. If there was a pure shift in N400 latency, with no reduction in amplitude, then the overall average amplitude of the N400 effect over a broad time window (200–1,200 ms after Task 2 word onset) should not depend on SOA. Consistent with this prediction, the overall amplitude did not vary significantly across SOAs (−0.513, −0.730, and −0.022 μV at the 100-, 300-, and 900-ms SOAs, respectively; $F < 1.0$) (see Figure 7). Thus, these data are consistent with a pure shift in the timing of the N400 effect.

In one minor respect, the results of Experiment 3 appear to differ from those of Experiment 1. The reduction of the amplitude of the N400 effect between the 300-ms SOA and the 900-ms SOA was only about 11% in this experiment, compared with a 52% reduction in Experiment 1. However, this apparent difference between experiments was not statistically significant, $F(1, 22) < 1.0$. In any case, the 300-ms SOA is intermediate (neither short enough to guarantee the presence of a bottleneck delay nor long enough to guarantee the absence of one), and so the relevant models do not make clear predictions for this SOA.

Experiment 4

The most straightforward explanation of Experiments 1–3, given the central bottleneck model, is that words cannot be processed semantically while central operations are devoted to another task. If this straightforward hypothesis is correct, then we should observe a full-sized N400 effect when the Task 2 word is presented well before Task 1 central operations begin. To test this prediction, we occasionally presented the Task 2 word 200 ms before the onset of the Task 1 auditory stimulus (i.e., at an SOA of –200 ms).

Method

Participants. There were 18 participants, drawn from the same participant pool as in the previous experiments. None had participated in the previous experiments. All of them were native English speakers and had normal or corrected-to-normal vision. As in Experiment 1, there were six versions of the unrelated word lists, counterbalanced across participants.

Apparatus, stimuli, and procedure. The tasks, stimuli, and equipment were the same as in Experiment 1, except that the 300-ms SOA was replaced with the –200 ms SOA. The SOAs were intermixed within blocks, as in previous experiments.

Results

The data analysis was similar to that of Experiment 1. Application of the RT cutoffs eliminated 1.36% of trials. Rejection of trials with ocular artifacts in the EEG data led to the further elimination of 14.42% of trials but no more than 25% of trials for any individual participant.

Behavioral data analyses. As in Experiments 1 and 3, the ANOVAs on RT and PE for Task 1 and Task 2 were conducted as a function of Task 2 context–target relatedness (related and unrelated) and SOA (–200, 100, and 900 ms). Figure 8 shows the mean RT and Table 4 shows the mean PE for Task 1 and Task 2 in each condition.

For Task 1, Mean RT1 increased as SOA decreased, $F(2, 34) = 4.17$, $p < .05$, $MSE = 10{,}674$, $\eta_p^2 = .20$; RT1 was 878, 852, and 809 ms at the –200-, 100-, and 900-ms SOAs, respectively. A similar effect was observed for PE1, $F(2, 34) = 15.16$, $p < .0001$, $MSE = 0.0003$, $\eta_p^2 = .47$; PE1 was .030, .018, and .007 at the –200-, 100-, and 900-ms SOAs, respectively. No other effects were statistically significant.

For Task 2, mean RT2 increased as SOA decreased, $F(2, 34) = 878.26$, $p < .0001$, $MSE = 5{,}668$, $\eta_p^2 = .98$; mean RT2 was 1,439, 1,107, and 696 ms at the –200-, 100-, and 900-ms SOAs, respectively. RT2 was 43 ms faster for related words than for unrelated words (i.e., the relatedness effect), $F(1, 17) = 28.43$, $p < .0001$, $MSE = 1{,}729$, $\eta_p^2 = .63$. The interaction between Task 2 relatedness and SOA was not significant ($F < 1.0$); the relatedness effect on RT2 was 41, 47, and 40 ms at the –200-, 100-, and 900-ms SOAs, respectively (see Figure 8).

As with RT2, PE2 increased as SOA decreased, $F(2, 34) = 10.75$, $p < .001$, $MSE = 0.0007$, $\eta_p^2 = .39$. PE2 was .042 smaller when the Task 2 target word was unrelated to the context word than when it was related, $F(1, 17) = 16.67$, $p < .001$, $MSE = 0.0028$, $\eta_p^2 = .49$. The interaction between the SOA and Task 2 relatedness was not significant ($F < 1.0$).

ERP analyses: Attenuation of the N400 effect. The results of the N400 effect amplitude analyses generally confirmed those of

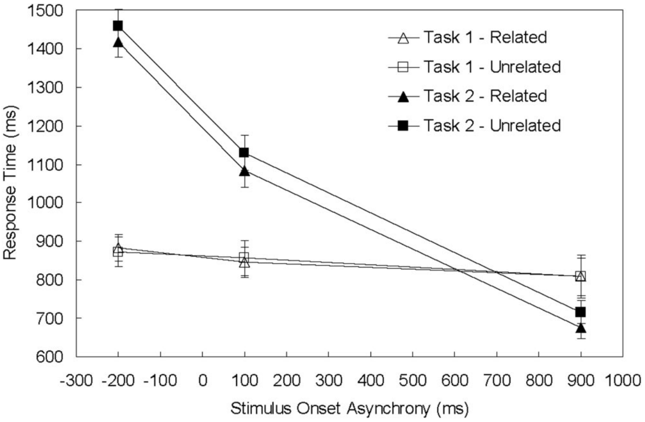

Figure 8. Mean response times for Task 1 and Task 2 in Experiment 4 as a function of Task 2 context–target relatedness (related and unrelated) and stimulus onset asynchrony (–200, 100, and 900 ms). Error bars represent the standard error of the mean (based on between-subjects variance in that condition).

Table 4
Proportion of Errors for Task 1 and Task 2 (Standard Error of the Mean in Parentheses) as a Function of Task 2 Context-Target Relatedness and Stimulus Onset Asynchrony in Experiment 4

Task 2 context-target relatedness	Stimulus onset asynchrony		
	−200 ms	100 ms	900 ms
	Task 1		
Related	.031 (.006)	.019 (.004)	.008 (.002)
Unrelated	.029 (.006)	.016 (.004)	.007 (.002)
	Task 2		
Related	.102 (.012)	.103 (.013)	.076 (.011)
Unrelated	.070 (.012)	.049 (.011)	.037 (.008)

Experiment 1. During the critical time window 300–500 ms after Task 2 word onset, the mean amplitude of the N400 effect differed across SOAs, $F(2, 34) = 39.55$, $p < .0001$, $MSE = 2.331$, $\eta_p^2 = .70$. Pairwise comparison revealed that the N400 effect was more negative (i.e., larger) at the 900-ms SOA (–5.039 μV) than at the –200-ms SOA (–1.176 μV), $F(1, 17) = 46.31$, $p < .0001$, $MSE = 5.798$, $\eta_p^2 = .73$, and the 100-ms SOA (–1.064 μV), $F(1, 17) = 71.21$, $p < .0001$, $MSE = 3.994$, $\eta_p^2 = .81$. There was no difference in amplitude between the two shorter SOAs (–200 ms and 100 ms; $F < 1.0$). In summary, a normal N400 effect was present at the 900-ms SOA but was strongly attenuated at both the –200-ms and 100-ms SOAs (see Figure 9).

ERP analyses: A temporal shift of the N400 effect. As in the previous experiments, we conducted fractional area latency analyses to look for a temporal shift in the N400 effect during the time window 200–1,200 ms after Task 2 word onset. Similar to Experiment 1, this analysis revealed that the latency of the N400 effect

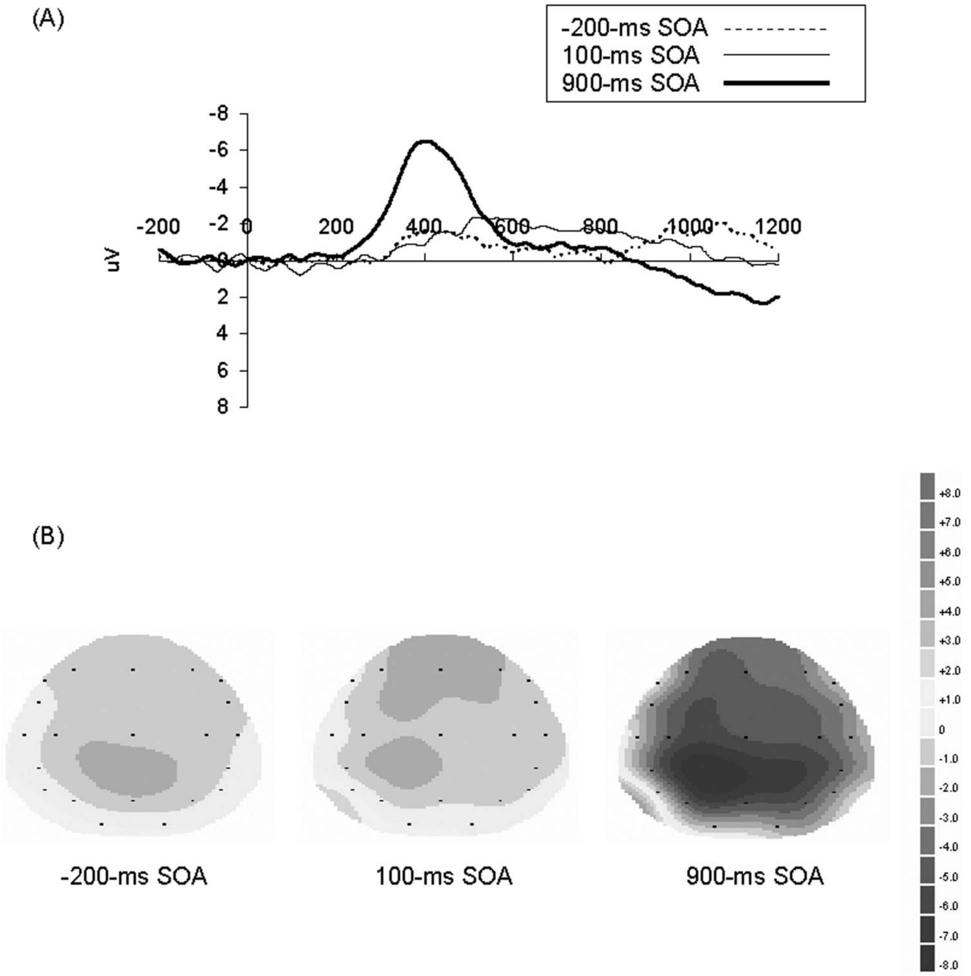

Figure 9. Grand average difference in event-related brain potentials, formed by subtracting semantically related Task 2 trials from semantically unrelated Task 2 trials (i.e., the N400 effect) in Experiment 4. Panel A shows the difference waveforms at the parietal electrode sites (data collapsed across the P3, Pz, and P4 electrodes). Negative is plotted upward and time zero represents Task 2 onset. The baseline period was the 200 ms prior to Task 2 stimulus onset. Panel B shows the scalp topography of the difference waveforms during the time window 300–500 ms after Task 2 word onset for each stimulus onset asynchrony (SOA).

differed across SOAs, $F_c(2, 34) = 22.39$, $p < .01$; the latency was 889, 646, and 395 ms at the –200-, 100-, and 900-ms SOAs, respectively. Pairwise comparisons revealed that the difference between the –200-ms SOA and the 900-ms SOA was significant, $F_c(1, 17) = 35.54$, $p < .01$, as was the difference between the –200-ms SOA and the 100-ms SOA, $F_c(1, 17) = 8.21$, $p < .05$. The difference between the 100-ms SOA and the 900-ms SOA was also significant, $F_c(1, 17) = 27.91$, $p < .01$ (see Figure 9).

Discussion

Experiment 4 examined whether the attenuation of the N400 effect at short SOAs is due specifically to the simultaneous engagement of central attention resources. The experimental design was similar to that of Experiment 1, except that the Task 2 target word appeared 200 ms *before* the onset of the Task 1 stimulus on some trials. With this 200-ms head start, there should have been sufficient time to deeply process the Task 2 word before Task 1 central processes began. Nevertheless, the N400 effect elicited by the Task 2 target word was still sharply attenuated at this SOA. In fact, the attenuation of the N400 effect during the critical time window (300–500 ms after Task 2 stimulus onset) did not differ between the –200-ms (76% attenuation) and 100-ms SOAs (85% attenuation; $F < 1.0$). Thus, the attenuation of the N400 effect cannot be attributed simply to the engagement of central resources by Task 1 central stages.

One alternative explanation for the N400 effect attenuation is that in this dual-task paradigm, participants strategically defer lexical and/or semantic processing of the Task 2 word. As noted by McCann et al. (2000), participants might apply top-down control over word processing to prevent it from interfering with the processing of the nonlexical Task 1. Assuming that this control is exerted in anticipation of the Task 1 stimulus, one would expect attenuation of the N400 effect even at the –200-ms SOA (as we observed). However, if such top-down strategic blocking is feasible in this paradigm, one would naturally expect people to be able to impose strategic blocking to the processing of irrelevant color words while naming colors in the Stroop paradigm as well. Nevertheless, the Stroop effect has been found to be robust even when the proportion of incongruent trials (and hence the incentive for blocking) is high. This discrepancy might reflect the fact that Task 1 and Task 2 in our dual-task experiments have very little overlap in stimulus–response features, whereas the irrelevant color word and relevant ink color in the Stroop paradigm have strong overlap in stimulus–response features (see the General Discussion for further discussion of this issue). Consequently, it may be more difficult to impose strategic blocking in the Stroop paradigm than in the dual-task paradigm.

A second explanation is that participants "reserve" central resources for the task expected to be performed first (Task 1), even before the stimulus arrives, making these resources unavailable to process the Task 2 word (see De Jong, 1995; Meyer & Kieras, 1997, for related ideas). This hypothesis readily explains why the attenuation of the N400 effect was obtained even when the Task 2 target word appeared 200 ms before the Task 1 stimulus. A real-life analogy is making a dinner reservation at a restaurant. The restaurant will not give your reserved seats to other customers who arrive before you, even if you have not yet arrived and those seats are therefore unoccupied.

As in the previous experiments, we also found that the latency of the N400 effect was longer at the 100-ms SOA (646 ms) than at the 900-ms SOA (395 ms). This finding supports the hypothesis that the generation of the N400 effect was suppressed until Task 1 central processing was completed. To see whether the N400 effect was shifted in time, at short SOAs, with no loss of total amplitude, we compared the overall amplitude (during the broad time window 200–1,200 ms after Task 2 stimulus onset) across SOAs. This analysis showed no effect of SOA ($F < 1.0$). The mean amplitude of the N400 effect was −0.850, −1.035, and −1.040 μV at the –200-, 100-, and 900-ms SOAs, respectively. These data are consistent with a pure shift in the timing of the N400 effect at short SOAs relative to long SOAs.

Experiment 5

In Experiments 1–4, we found evidence that semantic activation for a word requires central attention using the N400 effect, an index of *semantic* activation. These findings leave open the possibility that some component of word processing prior to semantic activation was able to overlap with Task 1 central processing (see Reynolds & Besner, 2006). The automaticity of lexical activation, but not semantic activation, would reconcile the present results with the conclusions of Cleland et al. (2006). They found that word frequency effects, an index of *lexical* activation, were partially underadditive with SOA and therefore concluded that lexical activation is automatic.

To determine whether lexical activation can occur without central attention, in Experiment 5 we used a word frequency manipulation in a lexical decision Task 2 (Task 1 remained the same as in Experiments 1–4). Participants were to indicate whether the string of letters formed a word or a nonword. As in previous behavioral studies, we examined whether word frequency effects on RT2 (for word trials only) were additive or underadditive with SOA. More important, we measured an ERP component known as the P3.

The P3 is a positive deflection in the ERP waveform that occurs roughly 400–600 ms after stimulus onset and is larger over parietal midline sites. Polich and Donchin (1988) found, in a single-task paradigm, that words that occur frequently in written English produce a larger P3 amplitude and a shorter P3 latency than words that occur less frequently.[3] The difference in P3 amplitude and latency between high- and low-frequency words (see Equation 2) did not depend on the probability of a stimulus being a word (assumed to affect response selection). Polich and Donchin argued that word frequency affects encoding processes and lexical access (modulating P3 amplitude and latency) but not the response selection and production phases of the lexical decision task.

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[3] Note that the effect of manipulations of word frequency (global frequency in the English language) on the P3 is opposite to that of manipulations of stimulus probability (local frequency within an experiment). P3 amplitude increases as target probability decreases (e.g., the oddball effect; see Duncan-Johnson & Donchin, 1977; Luck, 1998). In our Experiment 5, we manipulated word frequency, but the local frequency was constant across conditions (each word appeared only once within the experiment).

$$\text{P3 difference} = \text{high-frequency words ERP} - \text{low-frequency words ERP} \quad (2)$$

If lexical activation of the Task 2 word is postponed while participants select a response for Task 1, then the P3 difference should initially be attenuated at short SOAs and then possibly occur later in time (i.e., after Task 1 central operations have finished). However, if lexical activation is not subject to the central bottleneck and can proceed in parallel with Task 1 central operations, then the P3 difference elicited by the Task 2 word should be similar at short and long SOAs.

Method

Participants. There were 18 participants, drawn from the same participant pool as in the previous experiments. None had participated in the previous experiments. All of them were native English speakers and had normal or corrected-to-normal vision.

Apparatus, stimuli, and procedure. The tasks, stimuli, and equipment were the same as in Experiment 1, except that a lexical decision task was used as Task 2. The word stimuli were taken from the Kučera and Francis (1967) norms. The high-frequency words ranged from 109 to 1,016 occurrences per million, whereas the low-frequency words ranged from 10 to 30 occurrences. The nonwords were formed by changing one of the letters of a word stimulus (see Lien, Allen, et al., 2006, Appendixes A and B, for an example). Each word or nonword appeared only once during the experimental trials for an individual participant.

Each trial started with the plus sign (fixation) in the center of the screen for 1,200 ms, followed by the Task 1 auditory stimulus for 100 ms. After one of the three SOAs (100, 300, or 900 ms intermixed within blocks), the Task 2 stimulus appeared in the screen center and remained until participants had responded to both Task 1 and Task 2. The leftmost response-box button was assigned to words, and the rightmost button was assigned to nonwords. As in the previous experiments, the fixation for the next trial appeared 800 ms after the response for the previous trial. Each participant received 2 practice blocks of 48 trials each and 17 regular blocks of 96 trials each.

EEG recording and analyses. The EEG recording and analyses were similar to previous experiments, except as noted. The EEG activity was recorded from F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, O1, and O2. Difference waves were constructed by subtracting the ERP waveforms elicited by low-frequency Task 2 words from the ERP waveforms elicited by high-frequency Task 2 words (see Equation 2), using the Pz electrode only. We conducted data analyses on the mean amplitude and latency of this P3 difference during the time window from 400 to 600 ms after Task 2 stimulus onset (where the P3 amplitude was maximal at the long SOA) relative to the 200-ms baseline period prior to Task 2 stimulus onset.

Results

The data analysis was similar to that of Experiment 1. Application of the RT cutoffs eliminated 0.54% of trials. Rejection of trials with ocular artifacts in the EEG data led to the further elimination of 18% of trials but no more than 25% of trials for any individual participant.

Behavioral data analyses. Following previous studies (e.g., Allen et al., 2002; Cleland et al., 2006; Lien, Allen, et al., 2006; McCann et al., 2000), we conducted the ANOVA for words only. The ANOVAs were conducted as a function of Task 2 word frequency (high and low) and SOA (100, 300, and 900 ms). Figure 10 shows the mean RT and Table 5 shows the mean PE for Task 1 and Task 2 in each condition.

For Task 1, there was only a main effect of SOA on PE1, $F(2, 34) = 13.51$, $p < .0001$, $MSE = 0.0003$, $\eta_p^2 = .44$. PE1 was .041, .028, and .022 at the 100-, 300-, and 900-ms SOAs, respectively. No other effects on either RT1 or PE1 were statistically significant.

For Task 2, mean RT2 increased as SOA decreased, $F(2, 34) = 205.00$, $p < .0001$, $MSE = 3{,}833$, $\eta_p^2 = .92$; mean RT2 was 953, 798, and 658 ms at the 100-, 300-, and 900-ms SOAs, respectively. A PRP effect of 295 ms was obtained. This effect is similar to that obtained in previous studies using a Task 2 word frequency manipulation (e.g., 259 ms in both Experiment 1 of McCann et al., 2000, and Experiment 2 of Cleland et al., 2006). Averaged across SOAs, RT2 was 67 ms faster for high-frequency words than for low-frequency words (i.e., the word frequency effect), $F(1, 17) = 139.08$, $p < .0001$, $MSE = 868$, $\eta_p^2 = .89$. More important, the interaction between the Task 2 word frequency and SOA was significant, $F(2, 34) = 5.40$, $p < .05$, $MSE = 389$, $\eta_p^2 = .24$; the word frequency effect on RT2 was 64, 53, and 84 ms at the 100-, 300-, and 900-ms SOAs (see Figure 10). A pairwise comparison between the 100-ms SOA and the 900-ms SOA also showed a statistically significant difference in the word frequency effect, $F(1, 17) = 7.02$, $p < .05$, $MSE = 252$, $\eta_p^2 = .29$.

PE2 increased as SOA increased, $F(2, 34) = 5.55$, $p < .05$, $MSE = 0.0012$, $\eta_p^2 = .25$; PE2 was .075, .090, and .103 at the 100-, 300-, and 900-ms SOAs, respectively. PE2 was .096 smaller for high-frequency Task 2 words than for low-frequency words, $F(1, 17) = 68.22$, $p < .0001$, $MSE = 0.0036$, $\eta_p^2 = .80$. The

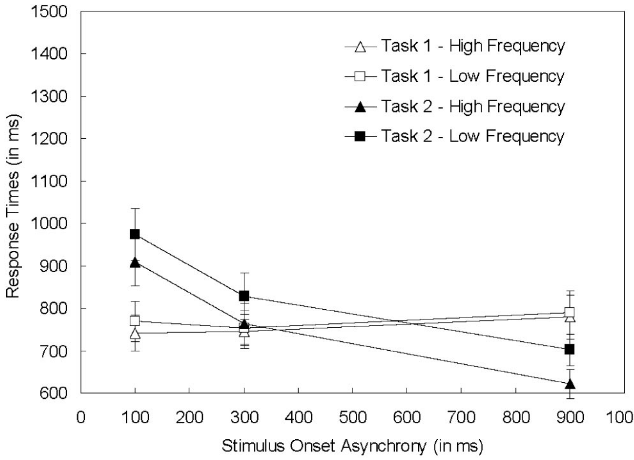

Figure 10. Mean response times for Task 1 and Task 2 in Experiment 5 as a function of Task 2 word frequency (high and low) and stimulus onset asynchrony (100, 300, and 900 ms). Error bars represent the standard error of the mean (based on between-subjects variance in that condition).

Table 5
Proportion of Errors for Task 1 and Task 2 (Standard Error of the Mean in Parentheses) as a Function of Task 2 Word Frequency and Stimulus Onset Asynchrony in Experiment 5

Task 2 word frequency	Stimulus onset asynchrony 100 ms	300 ms	900 ms
Task 1			
High	.044 (.007)	.025 (.005)	.021 (.006)
Low	.038 (.008)	.031 (.006)	.022 (.006)
Task 2			
High	.039 (.006)	.043 (.008)	.043 (.006)
Low	.112 (.012)	.137 (.016)	.162 (.021)

interaction between SOA and Task 2 word frequency was also significant, $F(2, 34) = 6.39$, $p < .01$, $MSE = 0.0008$, $\eta_p^2 = .27$; the word frequency effect on PE2 was .073, .095, and .120 at the 100-, 300-, and 900-ms SOAs, respectively.

ERP analyses: Attenuation of the P3 difference. The analysis of the amplitude of the P3 difference (see Equation 2) generally confirmed the N400 findings from Experiment 1. During the critical time window 400–600 ms after Task 2 stimulus onset, the mean amplitude of the P3 difference waveforms differed significantly across SOAs, $F(2, 34) = 4.83$, $p < .05$, $MSE = 2.324$, $\eta_p^2 = .22$. Pairwise comparisons revealed that the P3 difference at the 100-ms SOA (0.035 μV) was significantly smaller than at the 300-ms SOA (1.276 μV), $F(1, 17) = 4.47$, $p < .05$, $MSE = 6.198$, $\eta_p^2 = .21$, and at the 900-ms SOA (1.501 μV), $F(1, 17) = 25.43$, $p < .0001$, $MSE = 1.521$, $\eta_p^2 = .60$. However, the P3 difference was similar between the two longest SOAs (300 ms and 900 ms; $F < 1.0$) (see Figure 11). In summary, a large P3 difference was present at both the 300- and 900-ms SOAs but was strongly attenuated at the 100-ms SOA (by 97%). These findings suggest that some process leading up to Task 2 lexical activation cannot proceed in parallel with Task 1 central operations.

ERP analyses: A temporal shift of the P3 difference. As in the previous experiments, we also examined whether the effect of interest (in this case, the P3 difference between low- and high-frequency words) is simply reduced in magnitude or is also shifted in time. An examination of Figure 11 suggests that, contrary to what we found with the N400 effect, the P3 difference was simply attenuated at the 100-ms SOA; there is no sign of a delayed peak. Because of the virtual absence of the P3 difference at short SOAs, it is impossible to estimate its latency.[4]

Discussion

Experiment 5 used the P3 difference between low- and high-frequency words to examine whether Task 2 lexical access occurs while Task 1 central operations are still underway. This experiment was similar to previous behavioral dual-task studies on word recognition, except that we also measured the P3 difference associated with the word frequency manipulation. The behavioral data replicate the slight underadditive trend seen in previous studies (e.g., Lien, Allen, et al., 2006; McCann et al., 2000), which was statistically significant. However, the absorption into cognitive slack at the short SOA was not complete. Based on locus-of-slack logic, these data suggest that some lexical processes were delayed until after Task 1 central operations were completed.

The P3 data were consistent with the behavioral data. The amplitude of the P3 difference was reduced by 98% at the 100-ms SOA compared with the 900-ms SOA during the critical time window (400–600 ms post–Task 2 stimulus onset). Assuming that the P3 difference is generated by lexical activation (see Polich & Donchin, 1988), this finding supports the conclusion that lexical activation was attenuated at short SOAs.

There is no sign of a delayed P3 difference at the 100-ms SOA. This finding is intriguing, given that we did observe a delayed N400 effect in the earlier experiments. Because participants were clearly able to perform Task 2 accurately at all SOAs, it stands to reason that lexical activation did eventually occur. But, for reasons that are not entirely clear, the delayed lexical activation produced a similar P3 waveform for low- and high-frequency words. The present findings resemble those of Vogel at al. (1998), who manipulated the local frequency of different letters within an attentional blink paradigm. They observed a complete absence of the P3 difference at short lags—the effect did not emerge at a later point in time. Of course, this finding is somewhat less surprising in the attentional blink paradigm, in which the presentation of items after Target 2 might make it impossible to return to Target 2 processing later in time (e.g., owing to backward masking). In any case, the dramatic reduction of the P3 difference at the 100-ms SOA in our Experiment 5 implies that the Task 2 stage that

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[4] For the sake of completeness, we also conducted fractional area latency analyses (50% area latency measures) with the jackknife procedure on the latency of P3 difference during the time window 400–600 ms after Task 2 stimulus onset. This time window was used because the overall P3 difference at the short SOA over the broad time window (200 to 1,200 ms following stimulus onset as in Experiments 1–4) was essentially zero. It is impossible to measure the latency of a component that was not evident during that time period. Because there was at least a hint of a P3 at the short SOA between 400 and 600 ms (the total amplitude is positive), we decided to use that time window instead. This analysis showed that the latency of the P3 difference was significantly different across SOAs, $F_c(2, 34) = 43.69$, $p < .0001$; the latency was 466, 481, and 479 ms at the 100-, 300-, and 900-ms SOAs, respectively. The pairwise comparisons between the 100-ms and 300-ms SOAs, as well as between the 100-ms and 900-ms SOAs, were significant, F_cs$(2, 34) \geq 46.28$, ps $< .0001$. In contrast, the pairwise comparison between the 300-ms and 900-ms SOAs only approached significance, $F_c(2, 34) = 3.68$, $p = .07$. Even though there was a change in the P3 difference latencies across SOAs, the latency was slightly shorter at the 100-ms SOA than at the 300- and 900-ms SOAs. Thus, the direction is opposite to that predicted by the central bottleneck model, under the assumption that lexical activation by a word requires central attention.

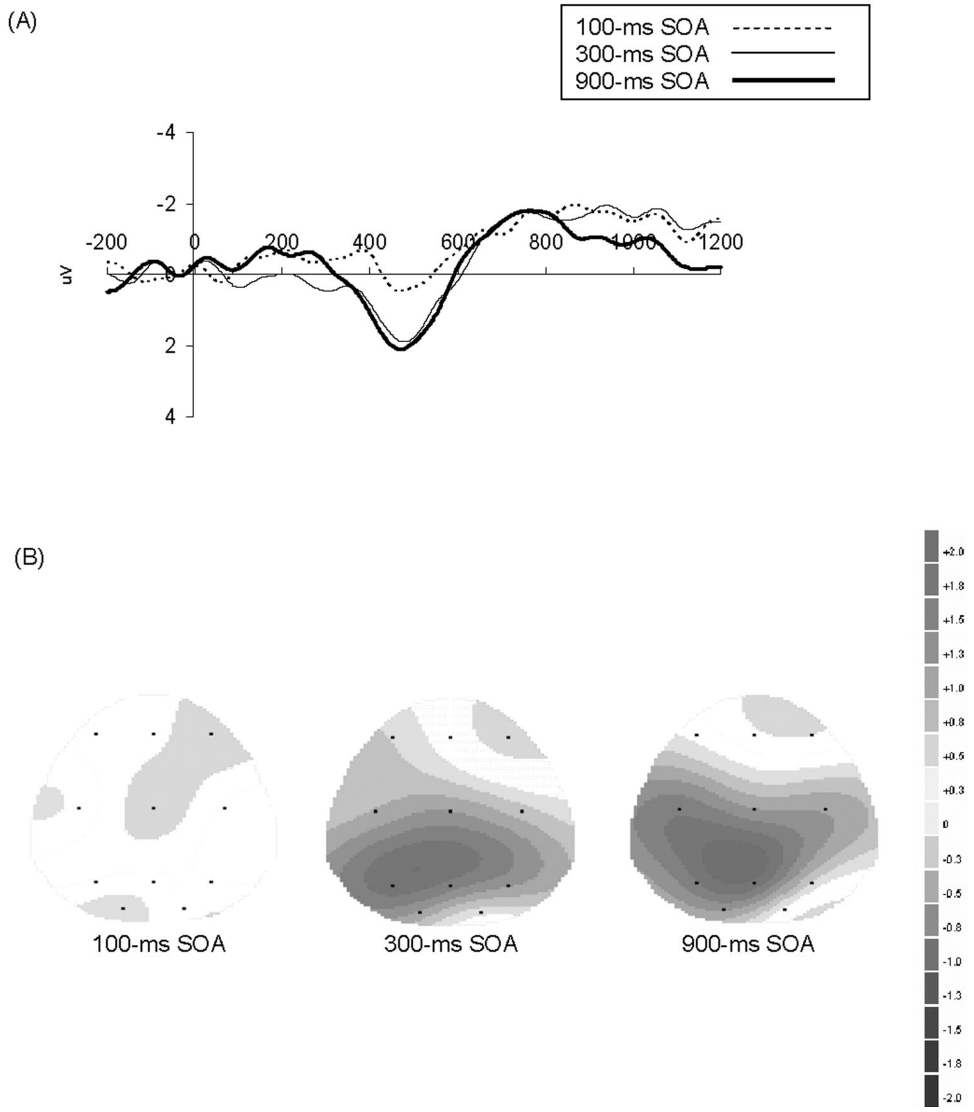

Figure 11. Grand average difference in event-related brain potentials, formed by subtracting Task 2 low-frequency trials from Task 2 high-frequency trials (i.e., the P3 difference) in Experiment 5. Panel A shows the difference waveforms at the Pz electrode. Negative is plotted upward and time zero represents Task 2 onset. The baseline period was the 200 ms prior to Task 2 stimulus onset. Panel B shows the scalp topography of the P3 difference waveforms during the time window 400–600 ms after Task 2 word onset for each stimulus onset asynchrony (SOA).

produces this difference (assumed to be lexical activation) is suppressed in the absence of central attention.[5]

General Discussion

The present study assessed the degree to which visual word processing occurs while central attention is devoted to another task. Previous dual-task approaches, relying on behavioral measures such as overall RT, have several drawbacks and have produced seemingly inconclusive results (e.g., Allen et al., 2002; Cleland et al., 2006; Lien, Allen, et al., 2006; McCann et al., 2000). To address this issue more directly, the present study relied on electrophysiological measures in a PRP paradigm. Experiments 1–4 measured the difference in the N400 elicited by Task 2 words

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[5] An alternative explanation of the Experiment 5 results is possible if one assumes that the stage that produces the P3 difference is not lexical activation but rather some later, nonlexical stage (contrary to Polich & Donchin, 1988). On this view, the absence of a delayed P3 difference at the short SOA could be interpreted as evidence that lexical activation did in fact occur during cognitive slack. In other words, by the time the post-bottleneck stage that produces the P3 difference is set to begin, low- and high-frequency words have already reached similar activation levels. A problem with this alternative account, however, is that it predicts no effect of word frequency on RT2 at the short SOA (in actuality this effect was 64 ms in our Experiment 5).

that were related or unrelated to the semantic context (an index of semantic processing). Experiment 5 measured the P3 difference between low- and high-frequency Task 2 words (an index of lexical access). The use of a difference wave to assess Task 2 word processing minimizes contamination from the overlapping ERPs from Task 1 processing.

The present study yielded four major findings. First, the initial N400 effect (300–500 ms after Task 2 stimulus onset) elicited by visual Task 2 target words was greatly attenuated at short SOAs relative to long SOAs. We obtained this result when the context word varied from trial to trial (in Experiments 1 and 4), extending Hohlfeld et al.'s (2004) findings with spoken words to visual words. We found the same result when the context word was fixed within a block (Experiment 3), minimizing the difficulty of retrieving the context word. Furthermore, we obtained evidence that the N400 effect was shifted in time at short SOAs. This finding is consistent with a central bottleneck that temporarily prevents semantic processing of the Task 2 word. As correctly noted by an anonymous reviewer, it is logically possible that the bottleneck is not in meaning extraction, per se, but rather in the comparison of word meaning with the current semantic context. Such a late bottleneck, however, could not easily explain the reduction in P3 difference amplitude observed in Experiment 5. It also could not easily explain why Vogel et al. (1998) found essentially no reduction or delay in the N400 effect in the attentional blink paradigm. Given that the attentional blink also seems to involve a central bottleneck (e.g., Jolicœur, 1999; Ruthruff & Pashler, 2001), there should have been complete suppression of the N400 effect in Vogel et al.'s study as well.

Second, no such attenuation of the N400 effect at short SOAs was found when the Task 1 stimulus was presented but did not require a response (Experiment 2). This finding indicates that the reduced initial N400 effect amplitude is primarily due to the absence of central resources, not the mere presence of a Task 1 stimulus.

Third, even when the Task 2 word was presented while central resources were not yet engaged (i.e., at the –200-ms SOA), the N400 effect was still sharply attenuated (Experiment 4). This result speaks to the general issue of central resource allocation (e.g., Pashler, 1984; Pashler & Johnston, 1989). Preparing to perform Task 1 (which was given higher priority than Task 2) may involve reserving central resources, making them unavailable to process the Task 2 word (see also Meyer & Kieras, 1997).

Fourth, we found that the effect of word frequency on the P3 difference, which is substantial at long SOAs, was nearly eliminated at the shortest SOA (Experiment 5). Taken together, these findings suggest that neither lexical activation (as indexed by the P3 difference) nor semantic activation (as indexed by the N400 effect) proceeded very far without central attention. Note that once one process has been blocked by the central bottleneck, no subsequent process (whether automatic or not) has any chance of proceeding in parallel with Task 1 central processes. This point leaves open the strange (and seemingly unlikely) possibility that some early processes (e.g., letter processing) are not automatic but later processes (e.g., lexical activation or semantic activation) are.

ERP Delay Versus RT2 Delay

The attenuation of the N400 effect and the P3 difference during the critical time window suggests that visual word processing is impaired while central attention is devoted to another task. In addition to the initial attenuation, we also found consistent evidence for an increase in the latency of the N400 effect at short SOAs relative to long SOAs. Such an increase in latency is roughly consistent with a central bottleneck that temporarily prevents word processing. It is interesting, therefore, to compare the delays estimated from the ERP data with the delays estimated from the RT2 data (which presumably also reflect a central bottleneck).

Table 6 shows RT2 and the latencies of the ERP components (the N400 effect and the P3 difference) for each SOA in Experiments 1–5. The RT2 values given in the table are based on participant medians, which are more closely analogous to measures of ERP latencies (see Luck, 2005). Across Experiments 1, 3, and 4, the average RT2 delay between the 100- and 900-ms SOAs was 385 ms. Meanwhile, in these same conditions, the average delay in the N400 effect was 208 ms. Thus, the delay in the N400, albeit substantial, was smaller than the delay in RT2.

One explanation for the difference is that ERP latencies and RTs are not directly comparable; it is common for ERP measures to produce smaller effect sizes than RT measures (see Luck, 2005, pp. 243–247, for detailed discussion of this issue). Another expla-

Table 6
Median Response Time for Task 2 (Median RT2) and the Latency of ERP Components (the N400 Effect in Experiments 1–4 and the P3 Difference in Experiment 5) at Each Stimulus Onset Asynchrony

Measure	Stimulus onset asynchrony				Delay
	−200 ms	100 ms	300 ms	900 ms	
		Experiment 1			
Median RT2		994	809	641	353
N400 latency		635	503	423	212
		Experiment 2			
Median RT2		670	654	638	32
N400 latency		450	403	434	16
		Experiment 3			
Median RT2		1,066	829	633	404
N400 latency		476	441	314	162
		Experiment 4			
Median RT2	1,378	1,037		640	397
N400 latency	889	646		395	251
		Experiment 5			
Median RT2		873	715	607	266
P3 latency		466	481	479	−13

Note. For all experiments, the delay was measured by subtracting the values at the 900-ms SOA from those at the 100-ms SOA. ERP = event-related potential; SOA = stimulus onset asynchrony.

nation is that whereas the N400 effect is sensitive primarily to the bottleneck delay, RT2 may be sensitive to the bottleneck delay plus other factors. For instance, reduced preparation at short SOAs may prolong response selection and/or response execution (see Jentzsch, Leuthold, & Ulrich, 2007; Pashler, 1994).

Possible Explanations for Incomplete Attenuation

The present experiments have shown that semantic activation (as reflected by the N400 effect) and lexical activation (as reflected by the P3 difference) were strongly attenuated while central attention is devoted to another task under dual-task conditions. Although the P3 difference was negligible at the 100-ms SOA, the initial amplitude of the N400 effect apparently was not eliminated completely (Experiments 1, 3, and 4). Furthermore, Experiment 5 showed a modest but statistically significant reduction in word frequency effects at short SOAs. Thus, the results suggest that some components of visual word processing take place in parallel with Task 1 central operations.

There are at least four specific explanations for why the N400 effect was not completely attenuated at short SOAs. First, it is possible that semantic activation for a word does require central resources but sometimes receives those resources before they are devoted to Task 1 at short SOAs. On these trials, one would expect little N400 reduction along with elevated RT1 (because the allocation of central resources to Task 1 was delayed). To explain the approximate size of the residual N400 effect at short SOAs, one would need to assume that this happened on about 45% of all trials. Presumably, it would happen more often for some participants than for others. Accordingly, we examined the RT1 data for 6 participants in Experiment 1 who exhibited the most slowing of RT1 at the 100-ms SOA relative to the 900-ms SOA and therefore were the best candidates to have stolen central resources from Task 1 to identify the Task 2 word. The reduction of the N400 effect at the 100-ms SOA relative to the 900-ms SOA at the parietal electrode sites (averaged across the P3, Pz, and P4 electrode sites) was no smaller for these 6 participants than for the other 6 participants; in fact, the trend went slightly in the opposite direction (73% vs. 36%, respectively), $t(10) = 1.81$, $p = .10$. Although the reduction was numerically smaller for participants with more RT1 slowing at short SOAs than for participants with less RT1 slowing in Experiment 3 (46% and 56%, respectively) and Experiment 4 (73% and 97%, respectively), the differences were small and not statistically significant, $ts(10) \leq 1.81$, $ps \geq .11$. Thus, our results do not support the hypothesis that the Task 2 words produce a nonzero N400 effect because they sometimes steal central resources away from Task 1. Also inconsistent with stealing resources from Task 1 is the finding of strong attenuation of semantic activation at the –200-ms SOA (Experiment 4). This finding suggests that Task 2 cannot utilize central resources even when they are unoccupied and there might be little or no cost to Task 1.

Second, the incomplete attenuation of the N400 effect at short SOAs might be due to central resource sharing between Task 1 and Task 2 (see Navon & Miller, 2002; Ruthruff, Pashler, & Hazeltine, 2003; Tombu & Jolicœur, 2003). For instance, participants in Experiment 1 might devote 55% of central resources to Task 1 and only 45% to Task 2, producing a proportionate (55%) reduction of the N400 effect elicited by Task 2 words at the 100-ms SOA. This hypothesis would predict longer RT1 at short SOAs than at long SOAs, consistent with our results. To account for the reduction of N400 effect at the –200-ms SOA in Experiment 4, one would need to add the assumption that central resource allocation to the two tasks was initially fixed (e.g., 76% for Task 1 and 24% for Task 2), regardless of which task appears first. This account has essentially the same problem as the previous account: Participants with the largest percentage of capacity allocated to Task 2 should show both greater slowing of RT1 and less attenuation of the N400 effect at short SOAs. As noted above, this pattern was not evident across the experiments.

Third, perhaps some components of word processing require central attention whereas others do not. This hypothesis is consistent with the claim that word processing is not monolithic but rather contains multiple, distinct processes (e.g., visual feature and letter processing, multiletter analysis, orthographic lexicon, phonological coding, semantic analysis; see Coltheart et al., 2001; Mayall et al., 2001). Evidence that some components require central attention whereas others do not was provided by a recent PRP study by Reynolds and Besner (2006). Using locus-of-slack logic, they found evidence that word processes up to the orthographic input lexicon do not require central attention but that processes after this stage (e.g., phonological recoding) do require central attention. This account could explain the underadditive trend between the effects of word frequency and SOA in previous behavioral studies (e.g., Cleland et al., 2006) and the present Experiment 5. However, this type of account has difficulty explaining why some semantic activation (presumably a very late component of word processing) still occurred without central attention (as indicated by the N400 effect). Once the earlier stages of word processing are blocked, it seems unlikely that later stages would be more successful.

Fourth, some especially skilled readers might be able to process the Task 2 word without central resources (at least some of the time), producing little or no attenuation of the N400 effect. Recently, Lien, Allen, et al. (2006; see also Allen et al., 2002) reported behavioral evidence that word recognition on Task 2 can proceed while central attention is devoted to Task 1 for older adults, who generally have relatively high Vocabulary scores on the Wechsler Adult Intelligence Scale—Revised, but not for younger adults, who generally have relatively low Vocabulary scores. They concluded that as word recognition skill reaches a certain point (achieved by many older adults), individuals are capable of performing word recognition in parallel with other tasks. A further study by Ruthruff, Allen, Lien, and Grabbe (in press) showed that the ability to identify words while central attention is devoted to another task strongly depends on individual reading ability. They argued that some individual participants with greater word-reading skill could process words with little or no central attention resources, whereas most others could not. The same hypothesis could nicely account for the present results as well. Note that this hypothesis could not be directly tested in the present study because of the small sample size and the fact that we did not assess reading ability. Further study is therefore required.

Relation to Stroop Studies

The claim that word processing requires central attention, based on our ERP findings, appears to conflict with the conclusions from traditional Stroop studies (e.g., MacLeod, 1991). In these studies, people cannot avoid reading the irrelevant color word while they are performing the color-naming task. Thus, contrary to our present findings, Stroop data suggest that words can be identified and processed up to the semantic level while central attention is engaged with a different task (i.e., color naming).

However, there is reason to believe that the single-task Stroop paradigm is a special case. Fagot and Pashler (1992), for instance, had participants perform a Stroop color-naming Task 2 with an auditory Task 1 in a dual-task paradigm. If word recognition is automatic, then the most plausible outcome would be an underadditive interaction between the effects of congruency and SOA. The reason is that at short SOAs, the words would be identified but these representations would then have several hundred milliseconds to decay (during the long bottleneck delay). By the time response selection for the color-naming task (the stage thought to be influenced by compatibility in the Stroop task; see Lu & Proctor, 1995) begins, the decayed representation of the color word should have less influence (compared with a long SOA, where there is no opportunity for decay). Contrary to this prediction, Fagot and Pashler observed additivity between the Stroop effect and SOA, supporting our conclusion that word processing requires central attention.

One speculative explanation for this discrepancy between dual-task studies and traditional Stroop studies is that participants find it more difficult to block word processing in the single-task Stroop paradigm because the tasks (color naming and color-word reading) are so closely related. In the dual-task paradigm, however, central operations between tasks are more distinct (e.g., a tone discrimination for Task 1 vs. Stroop color naming for Task 2 in Fagot & Pashler, 1992; or a tone discrimination for Task 1 vs. a semantic relatedness judgment for Task 2 in our study). This distinctness might make it easier for participants to block Task 2 (see Lien, Ruthruff, Hsieh, & Yu, 2007, for a similar argument).

Another explanation is that although word processing does rely on central attention, some word processing can be accomplished without central attention. The amount that is accomplished might be sufficient to cause a Stroop effect (in a single-task paradigm) and a nonzero N400 effect at short SOAs (in our dual-task paradigm). Also, note that the Stroop paradigm uses the same small set of words (often two to four) again and again, whereas the present study used a relatively large set of words (360 target words in Experiments 1–4 and 816 words in Experiment 5) presented only once or twice each during an experimental session. Perhaps less central attention is needed to process words that are highly primed and have very high local frequency.

Another study relevant to the present work is Dell'Acqua, Job, Peressotti, and Pascali (2007). Although they did not use a Stroop paradigm per se, they did use a Stroop-like paradigm with picture and word stimuli. They found that Task 2 picture naming was slowed by a semantically related distractor word (e.g., slow response to name the picture of a bed in the presence of the distracting word *couch*). Critically, this effect was underadditive with SOA, opposite to the findings of Fagot and Pashler (1992) using Stroop stimuli. The authors therefore proposed that semantic activation from the word occurred without central attention at short SOAs and then decayed during the bottleneck delay. However, note that the long bottleneck delay at short SOAs gave participants time to adopt a much sharper focus of spatial attention than is possible at long SOAs (see also Cohen & Magen, 2004). Accordingly, the reduced effect at short SOAs might simply reflect a sharper focus of spatial attention (see Lachter, Forster, & Ruthruff, 2004, for a summary of evidence that word processing requires spatial attention). Note that the hypothesized sharpening was impossible in Fagot and Pashler, because the color and word were part of the same physical object. Thus, this explanation can reconcile the discrepant findings between Dell'Acqua et al. and Fagot and Pashler.

Relation to Attentional Blink Studies

The current findings also have strong implications for the relation between the attentional blink effect and the PRP effect. As discussed in the introduction, Vogel et al. (1998; Experiment 2) found that in a rapid serial visual presentation, a word (Target 2) appearing shortly after a digit (Target 1) still produced a robust N400 effect. This was true even when people could not report the identity of the word, owing to the attentional blink. These findings suggest that participants successfully identified the visual word stimuli in parallel with the mental operations engaged by the first target (e.g., short-term memory consolidation). Using the PRP paradigm, however, we found that the N400 effect elicited by a Task 2 word was strongly attenuated (by about 55%–75%) when central operations were already engaged by another task (Task 1). Although it has been previously claimed that the attentional blink effect and the PRP effect both reflect the same central bottleneck resource limitation (e.g., Jolicœur, 1999; Ruthruff & Pashler, 2001), these contrasting findings suggest otherwise.

The discrepancy between the findings in the attentional blink paradigm (as in Vogel et al., 1998) and the PRP paradigm (as in the present study) might indicate that these effects reflect distinct resource limitations. The bottleneck in the attentional blink paradigm has been attributed to the process of memory consolidation (e.g., Jolicoeur, 1999), whereas the bottleneck in the PRP paradigm has been attributed to response selection (e.g., Pashler, 1984). These processes might rely on somewhat different sets of mental resources. For example, response selection might use the same resources as word identification whereas memory consolidation might not.

Conclusions

The present study assessed the automaticity of visual word processing using electrophysiological measures (i.e., the N400 effect and the P3 difference). The N400 effect is a powerful tool for assessing the degree of semantic activation of visual words, and the P3 difference is useful for assessing the degree of lexical activation. Unlike behavioral measures, such as overall RT, these ERP measures provide a specific, continuous indicator of word processing. Thus, they allow for a much more direct assessment of the time course of word processing. Using these measures, we found that the N400 effect and the P3 difference elicited by the Task 2 target word were strongly attenuated at short SOAs when central attention was devoted to Task 1. Thus, one contribution of this study is converging evidence that at least some components of visual word processing leading up to lexical activation and semantic activation are not automatic, in the sense that they require central attention.

Another important contribution of this study is the finding that even when central resources are not yet occupied by Task 1 (i.e., the –200-ms SOA condition in Experiment 4), the N400 effect elicited by the Task 2 word was still strongly attenuated. We propose that participants commit central resources to the task expected to be performed first, even before the stimulus arrives, making those resources unavailable to other tasks.

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Appendix

Category Labels and Members Used in Experiment 3

Column headings are the category labels. The unrelated words were selected from different categories, with the restriction that each word appear exactly once in the related condition and once in the unrelated condition.

Mammals	Body parts	Vehicles	Birds	Bugs
gorilla	ear	scooter	hawk	gnat
pig	tongue	cart	pigeon	moth
deer	thumb	truck	duck	bee
zebra	heel	plane	turkey	wasp
rabbit	foot	yacht	sparrow	worm
dog	leg	car	robin	ant
sheep	eye	trailer	raven	cricket
wolf	neck	ship	seagull	termite
tiger	head	wagon	crane	beetle
bull	elbow	tram	swan	hornet
beaver	wrist	sled	finch	tick
coyote	cheek	canoe	parrot	aphid
bear	knee	van	chicken	flea
horse	toe	train	crow	spider
goat	ankle	bike	peacock	fly
cat	arm	boat	goose	roach
monkey	jaw	bus	eagle	ladybug
cow	finger	trolley	dove	maggot

Clothing	Family members	Shapes	Fruit	Vegetables
shorts	cousin	round	guava	beans
cap	child	crooked	lime	potato
shoe	niece	oval	pear	lettuce
boot	nephew	hexagon	banana	onion
robe	wife	ellipse	fig	pepper
hat	mother	circle	apple	carrot
glove	mom	pyramid	apricot	spinach
jacket	dad	cube	berry	pumpkin
skirt	sister	diamond	cherry	radish
jeans	sibling	jagged	mango	leek
sock	uncle	star	grape	cabbage
sweater	parent	line	kiwi	pea
hose	aunt	octagon	plum	turnip
shirt	father	box	coconut	sprouts
dress	son	sphere	lemon	yam
coat	grandpa	cone	melon	corn
pants	brother	square	peach	squash
scarf	husband	curved	papaya	celery

Flowers/trees/plants	Furniture	Occupations	Money	Room/place in a house
grass	futon	actor	euro	patio
cedar	dresser	janitor	bill	doorway
rose	chair	doctor	dollar	sunroom
elm	table	lawyer	buck	garage
ash	cabinet	clerk	loan	cellar
walnut	armoire	artist	cash	kitchen
maple	bed	farmer	dime	atrium
tulip	rocker	judge	stock	balcony
palm	stool	barber	debt	hallway
spruce	desk	teacher	quarter	pantry
redwood	hutch	manager	yen	foyer
fern	shelf	chef	credit	attic
oak	couch	baker	nickel	den
lily	stand	sailor	account	bedroom
cypress	chest	writer	pay	porch
willow	bench	waiter	check	deck
fir	sofa	nurse	penny	dining

Cooking tools	Geographical features	Weather	Colors	Fish
peeler	ocean	sleet	black	eel
fridge	stream	cold	white	sole
spatula	forest	rainbow	tan	perch
grill	desert	humid	silver	bass
toaster	beach	hail	yellow	halibut
knife	sea	cloudy	cyan	cod
faucet	canyon	thunder	gray	salmon
baster	pond	sunny	indigo	shark
sink	cave	monsoon	pink	carp
whisk	meadow	frost	violet	minnow
oven	cliff	rain	bronze	tuna
blender	lake	tornado	blue	sardine
mixer	valley	sky	green	marlin
grater	hill	storm	red	trout
pan	creek	foggy	maroon	guppy
stove	island	snow	brown	herring
pot	bay	hazy	gold	catfish

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