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Resolving Semantic Interference During Word Production Requires Central Attention

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Abstract

The semantic picture-word interference task has been used to diagnose how speakers resolve competition while selecting words for production. The attentional demands of this resolution process were assessed in two dual-task experiments (tone classification followed by picture naming). In Experiment 1, when pictures and distractor words were presented simultaneously, semantic interference was not observed when tasks maximally overlapped. This replicates a key finding from the literature that suggested that semantic picture-word interference does not require capacity-limited central attentional resources and occurs prior to lexical selection, an interpretation that runs counter to the claims of all major theories of word production. In another Experiment 1 condition, when distractors were presented 250 ms after pictures, interference emerged when tasks maximally overlapped. Together, these findings support an account in which interference resolution and lexical selection both require central resources, but the activation of lexical representations from written words does not. Subsequent analysis revealed that discrepant results obtained in previous replication attempts may be attributable to differences in phonological (ir)regularity between languages. In Experiment 2, degree of semantic interference was manipulated using the cumulative semantic interference paradigm. Interference was observed regardless of task overlap, confirming that lexical selection requires central resources. Together, these findings indicate that a lexical selection locus of semantic picture-word interference – and models of word production that assume such a locus – may be retained.

Keywords

lexical selection; picture-word interference; cumulative semantic interference; dual-task; psychological refractory period

A longstanding goal of cognitive psychology has been to determine how people are able to select a single response from among many alternatives. Nowhere is the set of possible responses larger than in the psycholinguistic domain. Estimates put the productive vocabulary size of a well-educated adult native speaker of English at around 30,000 words (Levelt, 1989). How is the language production system able to select the correct word from such a large set, and how does this selection process unfold over time?

Before addressing these questions, it is useful to situate them in the appropriate theoretical context: models of word production. Although different models disagree on specific processing assumptions regarding the spread of activation and the existence of competition between representations (e.g., Bloem & La Heij, 2003; Caramazza, 1997; Dell, 1986, 1988; Levelt, Roelofs, & Meyer, 1999), they largely agree on what the major stages of word

production are and how they are ordered. Before producing a word (e.g., “cat”), speakers must first identify the semantic content they wish to express (<IS A PET>, <MEOWS>). Next, they must determine which word representation, often termed the lemma, best communicates that content (*cat*). This process is known as lemma selection, and it is the stage of production with which questions regarding word selection are concerned. The phonemes of the selected lemma (/k/, /æ/, /t/) are retrieved during phoneme selection. Finally, speakers prepare their articulators to produce the retrieved phonemes, after which the word is uttered.

Models of the language production system rely heavily on data from two sources: speech errors, which provide qualitative data about where production processes can go wrong; and reaction time (RT) tasks, which provide quantitative data about the time course of those processes. One such RT task is picture-word interference (PWI), one of the workhorses of psycholinguistic research over the last 40 years (e.g., Glaser & Döngelhoff, 1984; Lupker, 1979; Rayner & Springer, 1986; Roelofs, 1992; Schriefers, Meyer, & Levelt, 1990). On each trial, participants are presented with a picture to name accompanied by a distractor word (either spoken or written) to ignore. By varying the relation of the distractor word to the lemma for the picture name as well as the distractor stimulus onset asynchrony (SOA) – that is, the delay between the onset of the picture and the onset of the word – it is possible to trace the time course of lexical access. For example, Glaser and Döngelhoff (1984) showed in a classic study that picture naming latencies are slower when a picture (e.g., APPLE) is accompanied by a same-category written distractor word (*peach*) than an unrelated distractor (*nickel*), but only when the word is presented at a distractor SOA between –100 ms and +100 ms. Though studies differ on the exact timing conditions under which semantically related distractors generate interference, they generally agree on a narrow window that includes a distractor SOA of 0 ms; outside that window, the interference disappears (e.g., Damian & Bowers, 2003; Damian & Martin, 1999; Starreveld & La Heij, 1996). As this semantic PWI is often thought to arise from competition between lemmas during lemma selection (e.g., Levelt et al., 1999; Roelofs, 1992; but see Mahon, Costa, Peterson, Vargas, & Caramazza, 2007), these results point to a critical window for the effect in which semantically related distractors are activated early enough to affect lemma selection, but not so early that they can be discounted by the language system prior to lemma selection.

In parallel with their efforts to study how different stages of word production (e.g., lemma selection and phoneme selection) unfold over time through the use of PWI experiments, language researchers have used the psychological refractory period (PRP) paradigm to determine their attentional requirements. According to the central bottleneck model of attention (Pashler, 1984; Welford, 1952), a prominent account of performance in dual-task experiments, tasks can be decomposed into three discrete, serially ordered stages of processing: perceptual encoding, in which a stimulus is apprehended; response selection, in which a response is chosen on the basis of the apprehended stimulus and rules that govern stimulus-response mappings; and response execution, in which the chosen response is manually prepared. Crucially, response selection (but not perceptual encoding or response execution) requires the use of indivisible, central (i.e., domain-general) attentional resources. When participants must produce independent responses to stimuli that are presented in close temporal proximity, the limited nature of these resources – which can only be allocated to response selection processing for one task at a time – gives rise to a processing bottleneck.

The effect of the bottleneck on dual-task processing is shown in Figure 1 (similar to, e.g., Ferreira & Pashler, 2002, Figure 2). When the stimuli for the two tasks are presented with a long delay between their onsets (i.e., at a long task SOA), Task 1 response selection has already been completed prior to the completion of Task 2 perceptual encoding (Figure 1a). This means that Task 2 response selection can begin after perceptual encoding without

delay. In contrast, when the stimuli for the two tasks are presented with only a short delay between their onsets (i.e., at a short task SOA), Task 2 perceptual encoding is completed before the completion of Task 1 response selection (Figure 1b). As Task 2 response selection requires the use of the same mental resources devoted to Task 1 response selection, it is delayed until Task 1 response selection finishes (represented by a dashed vertical line). This bottleneck creates cognitive “slack” during which no Task 2 processing occurs. Importantly for the present study, if the difficulty of Task 2 perceptual encoding were to increase by a moderate amount at a short task SOA, the added processing difficulty would be absorbed by the slack, and would not increase the Task 2 reaction time.

Semantic Picture-Word Interference: Perceptual or Post-Perceptual?

By applying the PRP paradigm to the study of word production, it is possible to determine the temporal locus and attentional requirements of each production stage (but see Roelofs & Piai, 2011). The same can be deduced for the semantic PWI effect. The first attempt to do so (Ferreira & Pashler, 2002, Experiment 2) exemplifies the methodology typical of such dual-task studies. Participants were presented with two stimuli on each trial (a picture-word stimulus followed by a tone) and instructed to respond to both in order as quickly as possible (by naming the picture and then pressing a button to identify the tone pitch as low or high). The relation of the word to the picture (*APPLE-peach* vs. *APPLE-nickel*) and the task SOA were varied to determine whether and when semantic interference affected reaction times (RTs) to each task.¹ Ferreira and Pashler found that pictures were named more slowly when accompanied by semantically related than unrelated distractors across all task SOAs, replicating the standard semantic PWI effect. More interestingly, this interference slowed tone discrimination latencies as well. According to the central bottleneck model, this indicates that semantic PWI must be resolved during either perceptual encoding or response selection, as an increase in duration of either stage would delay the completion of Task 1 response selection (the dashed vertical line in Figure 1b), which would in turn delay the commencement of Task 2 response selection and thus increase Task 2 RTs. In contrast, if semantic PWI were to resolve during response execution, tone discrimination latencies would have been unaffected by distractor relatedness.

To further pinpoint the locus of semantic PWI resolution, Dell’Acqua, Job, Peressotti, and Pascali (2007) reversed the order of tasks that had previously been used in dual-task picture naming studies. Participants in their experiment were presented with a tone followed by a picture-word stimulus, and had to perform tone discrimination before picture naming. Unsurprisingly, they found that when the picture and word were simultaneously presented either 1000 ms or 350 ms after the tone, participants named the picture more slowly when it was accompanied by a semantically related word than a semantically unrelated word – the standard semantic PWI effect. When the task SOA was reduced to 100 ms, however, the PWI effect disappeared completely. According to the logic of the central bottleneck model, this indicates that semantic PWI resolution occurs during perceptual encoding, as the interference would have persisted at the short task SOA if it had either a response selection or response execution locus. With a perceptual locus, the extra processing generated by a semantically related distractor would be absorbed by the slack created by the central bottleneck at a short task SOA (see Figure 2).

The finding that semantic PWI affects perceptual processing is theoretically important for at least two reasons. First, it poses a major challenge to prominent accounts of the task.

¹Note that task SOA is distinct from distractor SOA. In a dual-task experiment, task SOA represents the delay between the presentation of the Task 1 and Task 2 stimuli (here, the picture and the tone). In picture-word interference, distractor SOA represents the delay between the presentation of the picture and the distractor word.

WEAVER++ (Levett et al., 1999), a model of word production that has used PWI experiments to inform its assumptions about the time course of lexical access, posits that this interference is resolved during lemma selection. A different model of PWI, the Response Exclusion Hypothesis (Mahon et al., 2007), argues that interference is resolved after lemma selection. These are not minor assumptions: If research were to conclusively demonstrate that semantic interference is resolved prior to lemma selection, both the models and our understanding of how words are produced would need to be fundamentally revised.

Each model can account for a perceptual locus of semantic PWI resolution only if lemma selection occurs during perceptual encoding as well. However, as the stage at which a speaker decides which word to say, lemma selection would seem to be the very definition of a response selection process. As such, it is likely to have a post-perceptual locus. Combined with the finding that semantic PWI is resolved during perceptual encoding, this calls into question the assumptions of both WEAVER++ and the Response Exclusion Hypothesis.

A second implication of such a finding is that it suggests semantic PWI and the Stroop effect reflect different underlying cognitive processes. In each trial of the Stroop task (Stroop, 1935), participants are presented with a color word and must name the color of the ink in which that word is written, which is either congruent or incongruent with the identity of the word. Participants are slower to name the color when it is incongruent with the word (e.g., the word BLUE in red ink) than when the two are congruent (RED in red ink).

A number of similarities exist between the tasks. Both Stroop and semantic PWI require participants to ignore a written word from the same semantic category as a to-be-produced target. Furthermore, when participants are instead asked to read the word aloud, the effects of picture-word relatedness (in PWI) and color-word congruency (in Stroop) are minimal. For these reasons, as well as others, the same cognitive processes are often thought to underlie the two tasks (e.g., Roelofs, 2003; see MacLeod, 1991 for a review).

The attentional demands of the Stroop task were first assessed in a dual-task experiment conducted by Fagot and Pashler (1992, Experiment 7). In that experiment, participants categorized the pitch of a tone and then named the color of a Stroop stimulus. The word was presented either 50 ms before, or 50, 150 or 450 ms after, the tone. At every task SOA, participants demonstrated a robust Stroop effect, naming the color of the word substantially slower for incongruent stimuli than congruent ones. Crucially, the size of this effect did not interact with task SOA, indicating that the Stroop manipulation slows response selection (or response execution; but see Magen & Cohen, 2002, 2010 for an alternate interpretation). This contrasts with the results of Dell'Acqua, Job et al. (2007), who found an underadditive interaction between semantic PWI and task SOA, thereby indicating that semantic PWI affects a perceptual stage of processing. If resolving Stroop interference and resolving semantic PWI have different attentional requirements, the claim that they arise from the same cognitive processes is no longer tenable.

Given the implications for models of word production, picture-word interference and the Stroop effect, much rides on the claim that semantic PWI affects a perceptual stage of processing. Thus, before accepting that these models have been seriously challenged, it is worth considering whether other interpretations of Dell'Acqua, Job et al.'s (2007) results are possible (an approach also adopted by van Maanen, van Rijn, & Borst, 2009). This paper will evaluate the possibility that the underadditive interaction they found between semantic relatedness and task SOA was due to the fact that picture-word stimuli are processed differently in dual-task and single-task settings.

Treating Target Pictures and Distractor Words as Separate Stimuli

All of the papers that have used the central bottleneck model to describe picture-word interference in dual-task experiments have treated picture and word processing as part of the same task, jointly represented by single perceptual encoding, response selection and response execution stages (Ayora et al., 2011; Cook, 2007; Cook & Meyer, 2008; Dell'Acqua, Job et al., 2007; Ferreira & Pashler, 2002; Piai, Roelofs, & Schriefers, 2012; Schnur & Martin, 2012; see also Piai & Roelofs, 2013; van Maanen et al., 2009; van Maanen, van Rijn, & Taatgen, 2012). Although it is true that participants must only select a single response for the task – the name of the picture – it may be an oversimplification to assume that the picture and word are processed as a single stimulus, and thus that they have interdependent attentional demands.

In fact, evidence suggests that they are not. For the reasons noted above, selecting a lemma for production in picture naming may require central attentional resources (although this hypothesis is first confirmed in Experiment 2). In contrast, word reading may not require central resources. Reynolds and Besner (2006, Experiment 1) conducted a dual-task experiment with Task 1 tone discrimination and Task 2 single word naming in which words were repeated after a large number of intervening trials. Participants were faster to read repeated words aloud on trials in which the word was presented 750 ms after the tone, but there was no effect of repetition at a short task SOA of 50 ms. This underadditive interaction between repetition and task SOA indicates that the orthographic-lexical processing underlying this repetition priming can proceed in parallel with central resource-demanding tone processing, and thus that written forms do not require such resources to activate their lexical representations (see also Cleland, Gaskell, Quinlan, & Tamminen, 2006; Dell'Acqua, Pesciarelli, Jolicœur, Eimer, & Peressotti, 2007; Ruthruff, Allen, Lien, & Grabbe, 2008; but see Lien, Ruthruff, Cornett, Goodin, & Allen, 2008; McCann, Remington, & Van Selst, 2000).

The different attentional demands of processing the picture and word stimuli may interact in an unexpected way when PWI is the second task in a dual-task setting. At short task SOAs, picture naming processes that require central resources – including lemma selection – should be postponed until after the completion of Task 1 response selection, creating cognitive slack. However, because orthographic-lexical processing can occur even when central resources are already engaged, distractor processing should not be similarly postponed, as it could proceed simultaneously with Task 1 response selection (see Figure 3a). As a result, whereas the temporal proximity of distractor processing and lemma selection normally gives rise to semantic interference in a single-task setting or at long task SOAs in a dual-task setting, the distractor would be processed substantially earlier relative to lemma selection at short task SOAs. This would be functionally equivalent to presenting the distractor before the picture in a single-task setting, another manipulation that would cause the distractor to be processed earlier relative to lemma selection. The possibility that reducing task SOA affects semantic PWI performance in the same way as reducing distractor SOA due to the different attentional demands of picture naming and word reading will be referred to as the *differential automaticity hypothesis*.

The logic of this hypothesis, adapted from Besner, Reynolds, and O'Malley (2009), could account for the underadditive interaction between semantic relatedness and task SOA in the semantic PWI task. As noted, Glaser and Dünghoff (1984) found in a single-task experiment that same-category semantic distractor words only slowed picture naming relative to unrelated distractors when the word was presented between 100 ms before and 100 ms after the picture. Importantly, when the distractor was presented several hundred milliseconds before the picture, no effect of semantic relatedness was observed, presumably

because distractor activation had decayed prior to lemma selection. A short task SOA in a dual-task setting could lead to the elimination of semantic relatedness for the same reason, as central resource-demanding lemma selection would be postponed due to the central bottleneck and thus would occur too late to be affected by non-postponed distractor processing. Thus, it may not be the case that semantic PWI is absorbed into slack at a short task SOA (Dell'Acqua, Job et al., 2007); instead, the interference may never be generated in the first place.

Experiment 1

Under the differential automaticity hypothesis, when there is cognitive slack (i.e., at short task SOAs), decreasing either task SOA or distractor SOA by a particular length of time will reduce semantic PWI to the same extent. This is because both manipulations increase the delay between distractor word processing and lemma selection by the same amount. (In Figure 3a, decreasing task SOA would cause both Task 2 perceptual encoding and word processing to shift to the left, while decreasing distractor SOA would cause only word processing to shift to the left; either way, since lemma selection is subject to the central bottleneck, the delay between word processing and lemma selection would increase.) It follows that decreasing task SOA and increasing distractor SOA by the same length of time should have *no* effect on semantic PWI because the two manipulations should cancel each other out, leaving the timing of word processing unchanged. More generally, modifications to task SOA and distractor SOA are interchangeable as long as Task 2 processing is bottlenecked (i.e., there is cognitive slack). Thus, the chief determinant of whether or not semantic PWI emerges in such conditions should be the (signed) sum of the task SOA and the distractor SOA.

Experiment 1 tests this prediction by varying distractor SOA, presenting the word either simultaneously with the picture (i.e., at a 0 ms distractor SOA) or 250 ms after the picture. If semantic PWI disappears at short task SOAs because word processing occurs too early relative to lemma selection, delaying the presentation of the word relative to the picture should close the gap. This is best illustrated by comparing the short task SOA conditions in Figures 3a and 3b: At a short task SOA, increasing distractor SOA causes word processing and lemma selection to take place closer together in time, thereby re-introducing semantic interference.

Under this account, when the word and picture are presented simultaneously, semantic PWI should be evident only at long (1000 ms) and medial (350 ms) task SOAs, as Dell'Acqua, Job et al. (2007) showed. In contrast, when the word is presented 250 ms after the picture, semantic interference should not be evident at long and medial task SOAs because the distractor will be processed too late to affect lemma selection, but it should arise at a short task SOA (100 ms). This is due to the fact that pictures presented at a task SOA of 100 ms and a distractor SOA of 250 ms should show the same amount of semantic PWI as pictures presented at a task SOA of 350 ms and a distractor SOA of 0 ms, because the difference in time between distractor processing and lemma selection should be the same in both conditions ($100 + 250 = 350 + 0$).

Method

Participants—Forty-eight members of the University of California, San Diego community participated in Experiment 1. Participants received class credit for their participation. All reported English as their native language.

Apparatus—Stimuli were presented on an iMac computer running PsyScope X (Build 51; Cohen, MacWhinney, Flatt, & Provost, 1993; <http://psy.ck.sissa.it>). Three buttons on an

ioLab button box were used to collect responses to the tone task. A Shure SM10A headworn microphone connected to the button box measured voice onset latencies.

Materials—The picture-naming materials were taken from Damian and Martin (1999, Experiments 1 and 2). Ferreira and Pashler (2002, Experiment 2) used the same set of pictures, excluding one (*ring*) at random for counterbalancing reasons; the same picture was excluded here. The 27 pictures were line drawings of common objects. Two written distractors were selected for each picture: one that was a member of the same semantic category as the picture, and one that was semantically unrelated to the picture. Related and unrelated distractor sets were matched with respect to length in terms of both letters and phonemes. All materials are reported in Damian and Martin (1999).

The acoustic materials were taken from Dell'Acqua, Job et al. (2007). Low, medium and high tones were pure tones at frequencies of 300, 600 and 1200 Hz, each lasting 50 ms in duration.

Design and analysis—Experiment 1 included three independent variables: (a) task SOA (the picture was presented either 100, 350 or 1000 ms after the tone, as in Dell'Acqua, Job et al., 2007), (b) distractor SOA (the distractor was presented either 0 or 250 ms after the picture), and (c) distractor relatedness (semantically related or unrelated). Distractor SOA was manipulated between blocks, with the order of blocks counterbalanced across participants; task SOA and distractor relatedness were manipulated within block.

As in Ferreira and Pashler (2002), participants were presented with 162 trials in an order determined by one of six stimulus lists. Pictures were presented in the same fixed order in every list; however, the conditions in which a picture was presented on a particular trial were different in each list. Pictures were not fully crossed with conditions within participant because doing so would have necessitated doubling the number of trials; as a result, no participant named the same picture presented with both its related and unrelated distractors at the same combination of task SOA and distractor SOA. Instead, every picture was presented to each participant once at each of the six SOA combinations. Within these six presentations, it was paired with each of its two distractors once at each task SOA. Each combination of picture and distractor was presented to each participant once at one distractor SOA and twice at the other. Across the 48 participants, every picture was presented in every condition 24 times.

Procedure—Before beginning the experiment, participants practiced the tone discrimination and naming tasks in four practice blocks, similar to Ferreira and Pashler (2002). In the first block, they viewed each picture accompanied by its correct name. In the second block, the three tones were presented and labeled so participants could distinguish them. Then, they had to discriminate a series of 45 tones by pressing one of three buttons to identify each one as low, medium or high. Each of the 27 pictures was presented once in isolation in the third block and once again in the fourth practice block, when the two tasks were combined on each trial. Participants were told that their primary task was to identify the pitch of the tone, and that they should always do so before naming the picture. Participants who used the wrong name for a picture in any practice block were corrected.

Trials in the actual experiment were structured the same as in the fourth practice block. Each trial began with a fixation point presented for 1000 ms. After its offset, a 500 ms delay was followed by a randomly presented tone. Either 100, 350 or 1000 ms after the onset of the tone, a picture was presented until the voice key registered a response. A centered, written distractor word was presented in 24-point font either simultaneously with the picture or 250 ms after its onset. As in Damian and Martin (1999, Experiment 2) and Ferreira and Pashler

(2002, Experiment 2), the word was displayed for 200 ms, after which it was replaced by a visual mask (XXXXXXXX) for 500 ms. Because the word duration exceeded the threshold for conscious detection, the effect of the mask on semantic interference was likely modest (compare Damian & Martin, 1999, Experiments 1 and 2).

After the participant responded to both stimuli, the experimenter coded the accuracy of the vocal response and whether there was a voice key error, which arose when the microphone mistakenly recorded a response that was earlier or later than the actual onset of speech, or when the participant began an utterance with a filler word (e.g., “Um”). The next trial began 1500 ms after the experimenter coded the response. There were two blocks of 81 trials each (one for each distractor SOA), with a short break provided between blocks.

Results

In keeping with the participant exclusion procedures used by Schnur and Martin (2012), six participants were removed who made at least 20% errors in the tone discrimination task. In addition, another participant was removed who failed to follow instructions and responded to the picture before responding to the tone on at least 10% of trials.

The other 41 participants provided data for 6,642 trials, of which 87.5% (5,809) were analyzed. Trials were excluded when a participant responded to the stimuli out of order (38), or responded to the tone (343) or the picture (65) incorrectly; when the voice key failed to register the participant’s response at the appropriate time (151); or due to experimenter error (2). Among remaining trials, those in which participants responded to the tone faster than 300 ms (6) or slower than 2000 ms (6), or responded to the picture faster than 300 ms (7) or slower than 3000 ms (15), were excluded. In addition, trials in which a participant had an RT for either the tone discrimination task (151) or picture naming task (152) that was at least 2.5 standard deviations greater than their mean RT for the same combination of task, task SOA and distractor SOA were excluded. (Note that some trials violated multiple criteria.)

The mean reaction times for the tone discrimination (RT1) and naming tasks (RT2) were analyzed separately, each using two $3 \times 2 \times 2$ analyses of variance (ANOVAs) that treated participants ($F1$) and pictures ($F2$) as random variables. To assess the effects of distractor relatedness, planned comparisons were conducted within each combination of task SOA and distractor SOA. Variability is reported with 95% confidence interval halfwidths (Loftus & Masson, 1994).

Participants’ mean RTs to both tasks as a function of task SOA, distractor SOA and distractor relatedness are shown in Figure 4.

Task 1 performance—Participants responded to tones 37 ms slower on trials with the least task overlap than trials with maximal or medial overlap, indicated by a main effect of task SOA, $F1(2, 80) = 5.40$, $CI = \pm 26$ ms, $p = .006$; $F2(2, 52) = 34.1$, $CI = \pm 10$ ms, $p < .001$). No other factors or interactions affected tone discrimination latencies (all F s < 2.5 , all p s $> .12$).

Planned comparisons within each combination of task SOA and distractor SOA conditions revealed a potential effect of distractor relatedness only on trials in which the task SOA was 100 ms and the distractor SOA was 0 ms (henceforth referred to as the 100/0 condition), such that tones were responded to 20 ms slower when the picture and distractor were unrelated than when they were related. This effect was statistically significant only by participants, $F1(1, 80) = 4.07$, $CI = \pm 19$ ms, $p = .047$; $F2(1, 52) = 1.53$, $CI = \pm 41$ ms, $p = .222$; however, because this is the same combination of SOA conditions in which researchers

have found conflicting results concerning the effects of distractor relatedness in Task 2 picture naming, the implications of this 20 ms difference will be addressed in the Discussion. The effect of distractor relatedness was not significant in any other combination of SOA conditions (all F s < 2.3, all p s > .13).

Task 2 performance—A robust PRP effect was observed, such that participants named pictures 219 ms slower when they were presented 350 ms after tones than when they were presented 1000 ms after tones, and an additional 196 ms slower when they were presented 100 ms after tones. These differences reflect the postponement of Task 2 central resource-demanding processes that occurs when stimuli are presented closer in time, as indicated by a significant main effect of task SOA, $F(2, 80) = 278$, $CI = \pm 28$ ms, $p < .001$; $F(2, 52) = 1535$, $CI = \pm 12$ ms, $p < .001$. Participants also named pictures 20 ms slower when distractors were related than when they were unrelated, and 49 ms slower when distractors were presented simultaneously than when they were delayed, as indicated by significant main effects of distractor relatedness, $F(1, 40) = 18.9$, $CI = \pm 9$ ms, $p < .001$; $F(2, 26) = 21.2$, $CI = \pm 9$ ms, $p < .001$, and distractor SOA, respectively, $F(1, 40) = 50.1$, $CI = \pm 14$ ms, $p < .001$; $F(2, 26) = 100$, $CI = \pm 11$ ms, $p < .001$.

However, the size of this latter effect was not constant across task SOAs: As the stimuli were presented closer in time, the effect of distractor delay (collapsing across relatedness) decreased, as indicated by an interaction between task SOA and distractor SOA, $F(2, 80) = 38.4$, $CI = \pm 19$ ms, $p < .001$; $F(2, 52) = 63.9$, $CI = \pm 14$ ms, $p < .001$. Relative to pictures with simultaneously presented distractors, pictures with delayed distractors were named 103 ms faster at a 1000 ms task SOA, 56 ms faster at a 350 ms task SOA, and 13 ms slower at a 100 ms task SOA, though post hoc tests revealed that only the first two of those pairwise comparisons were statistically significant, 1000 ms: $F(1, 80) = 119$, $CI = \pm 19$ ms, $p < .001$; $F(2, 52) = 226$, $CI = \pm 14$ ms, $p < .001$; 350 ms: $F(1, 80) = 34.9$, $CI = \pm 19$ ms, $p < .001$; $F(2, 52) = 63.1$, $CI = \pm 14$ ms, $p < .001$; 100 ms: $F(1, 80) = 1.99$, $CI = \pm 19$ ms, $p = .162$; $F(2, 26) < 1$. In addition, there was a trend toward more semantic interference from related than unrelated distractors when the distractor was presented simultaneously (27 ms) than when the distractor was delayed (12 ms), as indicated by an interaction between distractor SOA and distractor relatedness that was marginally significant only by items, $F(1, 40) = 2.18$, $CI = \pm 14$ ms, $p = .150$; $F(2, 26) = 4.13$, $CI = \pm 14$ ms, $p = .053$. No other interactions affected picture naming latencies (all F s < 1.8, all p s > .18).

Planned comparisons were conducted to determine the timing conditions under which semantically related distractors interfered with picture naming. When distractors were presented simultaneously, semantic interference effects of 35 ms and 28 ms were observed when pictures were presented 1000 ms and 350 ms after tones, respectively, though this latter effect was marginally significant by items; 1000 ms: $F(1, 80) = 8.54$, $CI = \pm 24$ ms, $p = .005$; $F(2, 52) = 5.63$, $CI = \pm 35$ ms, $p = .021$; 350 ms: $F(1, 80) = 5.17$, $CI = \pm 24$ ms, $p = .026$; $F(2, 52) = 3.44$, $CI = \pm 35$ ms, $p = .069$. However, in the crucial condition in which pictures were presented only 100 ms after tones, the interference shrank to a non-significant 18 ms, $F(1, 80) = 2.16$, $CI = \pm 24$ ms, $p = .146$; $F(2, 26) < 1$. Statistically, this finding agrees with Dell'Acqua, Job et al. (2007) and Ayora et al. (2011), who found no interference from semantically related distractors at short task SOAs.

When distractors were presented 250 ms after pictures, non-significant semantic interference effects of -1 ms and 12 ms were observed when pictures were presented 1000 ms and 350 ms after tones, respectively, all F s < 1. This was expected, because the distractor was presented too late to affect picture-naming processes. However, when pictures were presented only 100 ms after tones, related distractors slowed picture naming by 26 ms

relative to unrelated distractors, though this effect was marginally significant by items, $F(1, 80) = 4.69$, $CI = \pm 24$ ms, $p = .033$; $F(1, 52) = 2.85$, $CI = \pm 35$ ms, $p = .097$.

In light of this predicted pattern of semantic interference – namely, that interference became non-significant at the short task SOA when words were presented simultaneously, but appeared at that same task SOA when words were delayed – it is surprising that a three-way interaction between task SOA, distractor SOA, and distractor relatedness was not observed. To increase statistical power, a post hoc contrast was conducted between the short and long task SOAs, comparing how task overlap affected the semantic interference effects differently for the two distractor SOAs. In essence, this is equivalent to computing the three-way interaction only across the short and long task SOAs. This contrast was marginally significant by both participants and by items, $F(1, 80) = 3.49$, $CI = \pm 12$ ms, $p = .065$; $F(1, 52) = 2.91$, $CI = \pm 17$ ms, $p = .094$, indicating that reducing task SOA from 1000 ms to 100 ms marginally affected semantic interference by different amounts for the two distractor SOAs – specifically, by reducing interference when distractors were presented simultaneously (Figure 3a) and by increasing interference when distractor presentation was delayed (Figure 3b).

Discussion

Experiment 1 showed that in a dual-task paradigm, simultaneously presented, semantically related distractor words interfered with picture naming except when they were presented 100 ms after tones. Conversely, semantically related distractor words presented after pictures interfered with picture naming *only* when they were presented 100 ms after tones. Furthermore, reducing task SOA from 1000 ms to 100 ms marginally affected semantic interference by different amounts at the two distractor SOAs. This pattern of data was predicted by an account that treats picture naming and word reading as two distinct tasks with dissociable attentional requirements, and – most importantly – it is compatible with accounts of semantic PWI that claim it occurs during (Levelt et al., 1999) or after (Mahon et al., 2007) lemma selection.

In addition to the expected main effects, there was a crossover interaction between task SOA and distractor SOA. Specifically, as task SOA decreased, increasing the overlap between tasks, the competition from delayed distractors (regardless of relatedness) increased more than the competition from simultaneously presented distractors, as evidenced by the steeper slopes for the RT2 curves in the right panel than in the left panel of Figure 4. This is important because it provides another source of evidence that, relative to simultaneously presented distractors, decreasing task SOA causes delayed distractors to be processed closer in time to central resource-demanding picture processing.

Consistent with this, it is worth noting that at every task SOA, RTs were slower in the distractor SOA condition that gave rise to more semantic interference, suggesting that both semantic interference and mean RTs were affected by the timing of distractor processing.² This relationship is concordant with the results of Glaser and Döngelhoff (1984), who found that both semantic interference and mean RTs peaked around a 0 ms distractor SOA. When they presented distractors simultaneously with the picture, compared with 300 ms after the picture, interference increased from 20 ms to 84 ms, and the mean RT for related and unrelated distractors increased from 614 ms to 752 ms.

²As noted, the 13-ms difference at the 100 ms task SOA was not significant. While this contradicts a prediction of the differential automaticity hypothesis, direct comparisons between different levels of distractor SOA may be confounded with other factors; for example, participants may simply have a harder time visually separating the picture and distractor when they are simultaneously presented.

The results of Experiment 1 may also be consistent with Dell'Acqua, Job et al.'s (2007) account. Under that account, semantic PWI is always generated when a related distractor is presented simultaneously with a picture, but this PWI is absorbed into slack at short task SOAs (see Figure 2). Although Dell'Acqua and colleagues did not manipulate distractor SOA or describe how such manipulations would be expected to affect picture naming latencies, it is reasonable to assume that delaying distractor presentation would similarly postpone semantic PWI resolution. Because PWI resolution is normally followed by cognitive slack, postponing that resolution would cause it to migrate across the slack. If the distractor SOA were long enough, the PWI resolution would begin to overlap with Task 1 response execution. At this point, because PWI resolution (under their account) must finish before lemma selection can begin, it would start to postpone Task 2 lemma selection, leading to an increase in picture naming latencies. Thus, the results of Experiment 1 do not necessarily rule out a locus of semantic PWI resolution that precedes lemma selection. However, as they also support interpretations that are consistent with existing models of the task (Levelt et al., 1999; Mahon et al., 2007), it is no longer necessary to fundamentally revise those models.

Nevertheless, several details slightly complicate this story. In particular, although the amount of semantic interference in the 100/0 condition did not reach statistical significance, the size of the effect was still 18 ms. This is closer in size to the effects observed in the 100/0 condition by Schnur and Martin (2012), who found significant semantic interference effects of 30 ms and 25 ms in two experiments, than it is to the effects observed by Dell'Acqua and colleagues, who found non-significant interference effects of -7 ms (Dell'Acqua, Job et al., 2007) and 2 ms (Ayora et al., 2011; Experiment 2). One possible reason for this, which hinges on the phonological regularity of the distractors, will be explored further in the General Discussion.

A further complication was the significant effect of semantic relatedness on the tone discrimination RTs in the 100/0 condition, which may have dampened the interference effect in picture naming. As tones were identified 20 ms faster when they were presented before pictures with related distractors than pictures with unrelated distractors, and RT1 and RT2 are tightly coupled at short task SOAs, that could have reduced the effect of semantic interference on picture naming latencies by 20 ms.

In most dual-task studies, RT1 effects would not necessarily change the interpretation of RT2 results. Some theoretical alternatives to the central bottleneck model claim that people can divide their central attentional resources between multiple tasks (e.g., Navon & Miller, 2002; Tombu & Jolicœur, 2003), allowing them to perform response selection for multiple tasks simultaneously. Counterintuitively, this capacity sharing causes RT1 to increase while leaving RT2 unchanged. This would normally mean that the difference in tone RTs in the 100/0 condition, which could be explained by positing that more capacity sharing occurred for unrelated distractors than for related distractors, could not be taken as evidence of a suppressed semantic interference effect in picture naming latencies.

However, that logic only applies when the stages of Task 2 are fixed in duration regardless of when they occur. If participants divided their attention between tasks in the present experiment, they would have (inefficiently) engaged in lemma selection at the same time as Task 1 response selection. On trials with simultaneously presented distractors, this would cause lemma selection to begin at the same time as in a single-task setting, bringing it closer in time to word processing. If this capacity sharing happened more often on trials with unrelated distractors, picture naming latencies on those trials might be relatively longer because the (unrelated) word would interfere more with lemma selection. Thus, even under a capacity sharing account, the effect of distractor relatedness on tone RTs would potentially

indicate a suppressed semantic interference effect on picture naming RTs, a possibility that cannot, at present, be ruled out.

Nevertheless, the existence of interference suppression in the 100/0 condition would not account for the semantic interference effect from delayed distractors that emerges at the shortest task SOA or the interaction between task SOA and distractor SOA. For these reasons, under both the central bottleneck model and capacity sharing models, the picture and distractor word are best treated as separate stimuli with dissociable attentional requirements as described above.

Experiment 2

Under the account advanced in Experiment 1, semantic PWI with simultaneously presented distractors leads to the dissipation of semantic interference at the shortest task SOA because picture naming requires central attentional resources and word processing does not. If this is true, manipulations of lemma selection difficulty that do not involve word reading should be equally robust at short and long task SOAs. This would confirm the assumption, heretofore untested, that lemma selection requires central attentional resources. Experiment 2 tests the attentional requirements of lemma selection by using a more straightforward manipulation of its difficulty: cumulative semantic interference (CSI).

In the standard CSI paradigm, participants name a series of pictures presented one at a time. Unbeknownst to participants, pictures presented (non-consecutively) throughout the experiment constitute semantic categories (e.g., farm animals: *cow*, *horse*, *donkey*, *sheep*, *pig*). Picture naming latencies increase, by an approximately linear amount, as a function of how many previous category members have been named. For example, participants who previously took 610 ms to name *cow* take 635 ms to name *horse*; later, they will take 661 ms to name *donkey* (Howard, Nickels, Coltheart, & Cole-Virtue, 2006). Although there is disagreement over how exactly cumulative semantic interference arises (Howard et al., 2006; Oppenheim, Dell, & Schwartz, 2010), all accounts agree that naming *cow* will slow the subsequent naming of *horse* during *horse*'s lemma selection. Thus, this paradigm can be used as the second task in a dual-task experiment to probe the attentional requirements of lemma selection.

If, as predicted, lemma selection requires central attentional resources, equal cumulative semantic interference effects will be observed at short and long task SOAs. If lemma selection does not require such resources, however, the interference effect will be absorbed into slack at the short task SOA, reducing or completely flattening the slope of the interference curve relative to the long task SOA.

Method

Participants—Forty new members of the University of California, San Diego community participated in Experiment 2.

Apparatus—The same apparatus used in Experiment 1 was used in Experiment 2.

Materials—The picture-naming materials for Experiment 2 were 94 line drawings of common objects. Nearly all of these (92) were selected from the International Picture Naming Project picture database (Bates et al., 2003); the other two were found online and drawn in a similar style. Of the 94 pictures, 60 critical pictures formed 12 categories of 5 items each (see Appendix). All categories, and 90% of the target names in each category, were used by Howard et al. (2006). Categories were chosen to minimize conceptual overlap

between them (e.g., there was only one category of animals). None of the 34 filler pictures belonged to any of the 12 categories.

The same acoustic materials used in Experiment 1 were used in Experiment 2.

Design and analysis—Experiment 2 included two independent variables: (a) task SOA (the picture was presented either 100 or 1000 ms after the tone), and (b) ordinal position (the picture was the first, second, third, fourth or fifth member of a semantic category presented within a given block). Both variables were manipulated within block.

In keeping with past experiments that used the cumulative semantic interference paradigm (e.g., Howard et al., 2006), the number of intervening pictures between category members (*lag*) was manipulated within each block. Within each category, pictures at consecutive ordinal positions were separated by 2, 4, 6 or 8 intervening pictures, with each of those lags represented once per category. Thus, the first and fifth picture from a category were always separated by exactly 23 intervening pictures (e.g., $6+1+2+1+4+1+8$). Each category in a block was assigned to one of twelve unique lag sequences (out of a possible 24; $4!$), and the order of categories within each block was counterbalanced across participants.

Every picture was presented once in each of two blocks, leading to 188 trials per participant. Within each block, all of the pictures in half of the categories, as well as half of the fillers, were presented at each task SOA. The task SOA of every picture switched between blocks. Across the 40 participants, every critical picture was supposed to be presented in every combination of block, ordinal position and task SOA four times; however, due to a counterbalancing error, 5% of combinations were presented two times and 5% of combinations were presented six times. Omitting these combinations did not affect either the pattern of data or any of the statistical analyses for picture naming latencies; thus, they are included in all analyses reported here.

Procedure—Before beginning the experiment, participants practiced the tone discrimination and naming tasks in two picture blocks. In the first block, participants practiced tone discrimination as in Experiment 1; however, in an attempt to reduce the frequency of tone errors, participants were given feedback when they pressed the wrong button. In the second block, participants practiced combining the tone task with the picture naming task in 54 trials (the same number of dual-task practice trials in Experiment 1). Half of the pictures were presented at each of the two task SOAs of 100 and 1000 ms. Practice pictures were not used in the experiment and did not belong to any of the 12 critical categories. As before, participants were told that their primary task was to identify the pitch of the tone.

Trials in the actual experiment were structured as in Experiment 1, except that only two task SOAs were used (100 and 1000 ms), and no distractors were presented. A short break was provided between the two blocks.

Results

Two participants were removed who made at least 20% errors in the tone discrimination task. In addition, another participant was removed who responded to the picture before responding to the tone on at least 10% of trials.

The other 37 participants provided data for 4,440 critical trials, of which 81.8% (3,631) were analyzed. Trials were excluded when a participant responded to the stimuli out of order (21), or responded to the tone (287) or the picture (235) incorrectly; when the voice key failed to register the participant's response at the appropriate time (101); or due to experimenter error

(13). Among remaining trials, those in which participants responded to the tone faster than 300 ms (1) or slower than 2000 ms (28), or responded to the picture faster than 300 ms (2) or slower than 3000 ms (9), were excluded. In addition, trials in which a participant had an RT for either the tone discrimination task (97) or picture naming task (84) that was at least 2.5 standard deviations greater than their mean RT for the same combination of task and task SOA were excluded. (Note that some trials violated multiple criteria.)

As the effect of block number did not interact either with ordinal position (coded either categorically or linearly; all $F_s < 2.5$, all $p_s > .12$) or with task SOA (all $F_s < 1.3$, all $p_s > .31$), data were averaged first within and then between blocks. The mean reaction times for the tone discrimination (RT1) and naming tasks (RT2) were analyzed separately, each using two 2×5 ANOVAs that treated participants ($F1$) and categories ($F2$) as random variables. To assess the linear effects of ordinal position, planned linear contrasts were conducted within each level of task SOA.

Participants' mean RTs to both tasks as a function of task SOA and ordinal position are shown in Figure 5.

Task 1 performance—Participants responded to tones 69 ms slower on trials with more task overlap, indicated by a main effect of task SOA, $F1(1, 36) = 29.4$, $CI = \pm 21$ ms, $p < .001$; $F2(1, 11) = 36.9$, $CI = \pm 21$ ms, $p < .001$. Ordinal position also affected tone discrimination latencies, $F1(4, 144) = 4.07$, $CI = \pm 15$ ms, $p = .004$; $F2(4, 44) = 4.43$, $CI = \pm 17$ ms, $p = .004$, but this effect did not interact with task SOA (both $F_s < 1$).

Planned linear contrasts within each level of task SOA assessed the linear effects of ordinal position, revealing that participants generally took longer to identify tones paired with pictures in higher ordinal positions. The average slowdown was 4.5 ms per position at a task SOA of 100 ms, which was significant only by categories, $F1(1, 144) = 1.90$, $CI = \pm 6.4$ ms, $p = .170$; $F2(1, 44) = 4.79$, $CI = \pm 6.8$ ms, $p = .034$, and 10.4 ms per position at a task SOA of 1000 ms, $F1(1, 144) = 10.2$, $CI = \pm 6.4$ ms, $p = .017$; $F2(1, 44) = 9.79$, $CI = \pm 6.8$ ms, $p = .003$. These slowdowns were not statistically different from each other, $F1(1, 144) = 1.64$, $CI = \pm 4.6$ ms, $p = .202$; $F2 < 1$.

Task 2 performance—Participants named pictures 389 ms slower when they were presented on trials with more task overlap, a robust PRP effect indicated by a main effect of task SOA, $F1(1, 36) = 261$, $CI = \pm 41$ ms, $p < .001$; $F2(1, 11) = 1191$, $CI = \pm 21$ ms, $p < .001$. Ordinal position also affected naming latencies, $F1(4, 144) = 10.5$, $CI = \pm 19$ ms, $p < .001$; $F2(4, 44) = 6.17$, $CI = \pm 28$ ms, $p < .001$, but did not do so differently across the two task SOAs (both $F_s < 1$).

Planned linear contrasts within each level of task SOA assessed the linear effects of ordinal position, revealing that participants took longer to name pictures in higher ordinal positions – the standard cumulative semantic interference effect. The average degree of interference was 11.8 ms per position at a task SOA of 100 ms, $F1(1, 144) = 8.28$, $CI = \pm 8.1$ ms, $p = .005$; $F2(1, 44) = 15.4$, $CI = \pm 7.5$ ms, $p < .001$, and 19.8 ms per position at a task SOA of 1000 ms, $F1(1, 144) = 23.2$, $CI = \pm 8.1$ ms, $p < .001$; $F2(1, 44) = 29.1$, $CI = \pm 7.5$ ms, $p < .001$. These interference effects were not statistically different from each other, $F(1, 144) = 1.89$, $CI = \pm 8.1$ ms, $p = .172$, $F(1, 44) = 1.09$, $CI = \pm 7.5$ ms, $p = .303$.

Given the unexpected slowdown in RT1 as ordinal position increased, the analogous slowdown in RT2 could potentially be attributable to extraneous factors, such as flagging attention, that would increase reaction times to both tasks. To demonstrate that a cumulative semantic interference effect above and beyond such factors exists, it would be sufficient to

show that the linear effect of ordinal position on RT2 is greater than on RT1. To compare them, the data were submitted to $2 \times 2 \times 5$ ANOVAs that additionally included task (tone discrimination vs. picture naming) as a factor, and the contrast weights that revealed linear effects of ordinal position on RT1 were subtracted from the contrast weights that revealed linear effects of ordinal position on RT2 within each level of task SOA. At a task SOA of 100 ms, the slowdown as ordinal position increased was greater for picture naming than for tone discrimination, though this difference was only marginally significant by participants, $F(1, 144) = 3.45$, $CI = \pm 3.9$ ms, $p = .065$; $F(1, 44) = 4.19$, $CI = \pm 3.5$ ms, $p = .047$. At a task SOA of 1000 ms, it was greater for picture naming both by participants and by categories, $F(1, 144) = 5.67$, $CI = \pm 3.9$ ms, $p = .019$; $F(1, 44) = 7.31$, $CI = \pm 3.5$ ms, $p = .010$. Thus, a cumulative semantic interference effect was evident at both task SOAs.

Discussion

Experiment 2 showed that in a dual-task paradigm in which pictures were presented after tones, a CSI effect emerged in naming latencies. Not surprisingly, this effect was present under conditions of minimal task overlap, in which the picture naming task was analogous to the standard CSI paradigm. Crucially, however, the effect was also present under conditions of maximal task overlap, when the stimuli were presented only 100 ms apart. Furthermore, the size of the interference effect was statistically equivalent across task SOAs. Because both accounts of the CSI effect agree that the interference slows lemma selection (Howard et al., 2006; Oppenheim et al., 2010), these findings indicate that lemma selection must be fully postponed due to the bottleneck, indicating a response selection or a response execution locus. As previous dual-task studies using picture naming as the first task have indicated a perceptual encoding or response selection locus of lemma selection (Cook, 2007, Experiment 1; Ferreira & Pashler, 2002), the only locus of lemma selection that agrees with all findings from dual-task studies is response selection. Thus, the results of Experiment 2 indicate that lemma selection requires central attentional resources.

Although the linear effect of ordinal position did not significantly interact with block number, the semantic interference effects did decrease between blocks, especially at the short task SOA. In the first block, the average slowdown per position was 18.0 ms at the 100 ms task SOA and 21.5 ms at the 1000 ms task SOA. In the second block, however, those slowdowns decreased to 5.6 ms and 19.8 ms, respectively (or 7.2 ms and 18.3 ms when category was treated as a random factor). This reduction in interference for pictures presented at the short task SOA in the second block (which were the same pictures presented at the long task SOA in the first block) appears to be the result of trial sequence, which becomes evident when the naming latencies are grouped based on the task SOA of the preceding trial. For trials in the second block that followed a short-SOA trial, the mean slowdown per position (with category treated as a random factor due to data sparsity when computing means for each participant) was 22.6 ms at the 100 ms task SOA and 20.6 ms at the 1000 ms task SOA. For trials that followed a long-SOA trial, those slowdowns decreased to 3.5 ms and 7.1 ms, respectively. Thus, the difference in CSI effects in the second block appears to result at least in part from the difference in frequency with which trials at each task SOA followed long-SOA trials: Among trials that contributed data to the analyses, trials at the 100 ms task SOA followed long-SOA trials 60% of the time, as opposed to 43% for trials at the 1000 ms task SOA. Although it is still not apparent why a preceding long-SOA trial should have diminished semantic interference so severely, it appears to have done so for both task SOAs.

One surprising aspect of the data was the existence of CSI-like effects not only on picture naming latencies, but on tone discrimination latencies as well. As noted above, this could have been due to participants slowing down over the course of the experiment. Indeed, in

mixed-effects models that included trial number within block as a covariate, trial number significantly predicted RTs in the tone discrimination task (but not the picture naming task).³

An alternate explanation is that, rather than completely postponing lemma selection until after completing tone discrimination, participants were engaging in capacity sharing. If people share capacity more when a secondary task is difficult, that could lead to an increase in RT1 while leaving RT2 unchanged (Tombu & Jolicœur, 2003). (Note that, unlike in Experiment 1, this logic holds for Experiment 2 because the difficulty of lemma selection on a given trial should not change regardless of whether it is performed simultaneously with, or delayed until after, Task 1 response selection.) Importantly, this would not change the interpretation of Experiment 2 results, as they could only be explained by a capacity sharing account if lemma selection requires central resources. However, sharing could have caused tone RTs to increase when picture naming was more difficult, creating the false appearance of a CSI effect on tone discrimination latencies. Such an account could hold even for the long task SOA: Because 13.5% (247/1829) of tone discrimination RTs at that task SOA were longer than 1000 ms, participants occasionally saw the picture before responding to the tone. If those trials are removed, the average slowdown in the 1000 ms task SOA condition as ordinal position increased changes to 3.5 ms per position for the tone discrimination latencies (down from 10.4 ms) and 18.2 ms per position for the picture naming latencies (down slightly from 19.8 ms). This suggests that the appearance of a CSI effect in tone discrimination latencies at the long task SOA can be attributed to the difficulty of picture naming on trials with task overlap, rather than nuisance factors that increased reaction times to both stimuli as the experiment progressed. Although it is not possible to do an analogous analysis for the 100 ms task SOA condition, as participants saw the picture before responding to the tone on every trial, it is reasonable to assume that the tone discrimination latencies in that condition were similarly affected. Thus, the magnitude of the CSI effects in Experiment 2 should be construed not as the difference between the effects of ordinal position on the picture naming and tone discrimination RTs, but solely as the effects of ordinal position on picture naming RTs.

General Discussion

Since 2002 (Ferreira & Pashler, 2002), dual-task experiments have been used in combination with PWI to shed light on how stages of word production can be organized into serially ordered, higher-level processes. Dell'Acqua, Job et al. (2007) presented participants with tones followed by pictures that were accompanied by simultaneously presented visual distractors, and found that semantic interference from related distractors disappeared at a short task SOA. As they assumed that lemma selection required the use of central attentional resources, they interpreted these results to mean that, contrary to the predictions of a prominent model of lexical production (Levett et al., 1999) and a task model of PWI (Mahon et al., 2007), the semantic PWI was resolved prior to lemma selection – that is, the interference was absorbed into slack and resolved concurrently with central resource-demanding tone processing.

³The data included in the ANOVAs were submitted to two mixed-effects models – one for each task – that included fixed effects of trial number within block (a continuous variable) and all main effects and interactions of block number, task SOA and ordinal position (also as a continuous variable). The models also included random factors for participants, categories and pictures, as well as interactions between every fixed effect (except trial number) and each random factor. In accordance with common practice for large data sets, absolute t values greater than or equal to 1.96 are taken to indicate statistical significance. All predictors were centered. Tone discrimination latencies were significantly slower at higher trial numbers within each block, $\beta = 6.4$, $t = 4.4$, and at the shorter task SOA, $\beta = -63.1$, $t = -3.4$, but were not affected by any other main effects or interactions (all t s < 1.1). Replicating the results of the ANOVAs, pictures were named more slowly in the first block, $\beta = -70.3$, $t = -3.6$, at the shorter task SOA, $\beta = -385.4$, $t = -15.3$, and at higher ordinal positions, $\beta = 14.6$, $t = 2.4$, but were not affected by any other main effects or interactions, including the critical interaction between task SOA and ordinal position (all t s < 0.7).

Experiments 1 and 2 suggest another interpretation that is consistent not only with the experimental results of Dell'Acqua, Job et al. (2007), but also with existing accounts of the task. They demonstrate that the diminution of semantic interference at a short task SOA is consistent with an account in which semantic PWI is resolved during or after lemma selection. Under the differential automaticity hypothesis, word processing – but not lemma selection, as Experiment 2 showed – can be performed concurrently with central resource-demanding tone processing. When the word and picture are simultaneously displayed shortly after the onset of the tone, this dichotomy causes word processing to occur earlier relative to lemma selection than usual, allowing extra time for the distractor lemma activation to decay and leading to a reduction in semantic PWI. When distractor presentation is delayed relative to picture onset, this temporal separation is reduced at short task SOAs, causing word processing and lemma selection to occur closer together in time and – as Experiment 1 showed – leading to the re-emergence of PWI. As this finding can be accounted for by both the central bottleneck model and capacity sharing accounts of dual-task performance, and is consistent with any account of PWI that predicts greater semantic interference when word processing and lemma selection occur closer together in time (Levelt et al., 1999; Mahon et al., 2007), it is no longer necessary to take the results of Dell'Acqua, Job et al. (2007) as evidence that semantic PWI resolution precedes lemma selection.

Accounting for other PRP experiment data

Given the apparent similarities between semantic PWI and the Stroop task, the proposed account of semantic PWI in dual-task experiments raises an obvious question: If competition between distractor processing and picture processing was reduced at a short task SOA due to differences in the attentional requirements of word reading and lemma selection, why was the same effect not observed in the Stroop task (Fagot & Pashler, 1992)? To answer this question, it is necessary to consider a number of interrelated differences between the standard Stroop and PWI experiment designs that may affect the magnitude and duration of semantic interference: differences in the size of the response set and the degree of stimulus repetition, differences in the degree of overlap between the distractor set and response set, and differences in the number of semantic categories represented in the response set. Although these differences will initially be considered independently, there is reason to believe that they interact in an important way, as will be demonstrated by an analysis of data collected by Piai et al. (2012).

First, there were differences in the size of the response set and in the frequency of stimulus repetition between the two tasks. Fagot and Pashler (1992) used three colors and three words, repeating each 224 times to each participant during the experiment. In contrast, Dell'Acqua, Job et al. (2007) used 48 pictures, each of which was repeated six times, and 96 words, each of which was repeated three times. La Heij and van den Hof (1995) explored the effects of these manipulations on the size of semantic PWI effects by repeatedly presenting pictures within blocks of trials. When blocks contained only four unique pictures, participants showed semantic interference effects of 3 ms, as compared with 12 ms when blocks contained twelve unique pictures. Furthermore, semantic interference was greater during the first half of the experiment than during the second half. Thus, all else being equal, these data suggest that interference should be larger when response sets are larger and when items are repeated fewer times.

Second, the distractor words and color names overlapped in the Stroop task – in fact, they were identical – whereas picture names and distractor words did not overlap in the PWI task. Either because of response priming or because it is difficult to discount task-relevant responses (Cohen, Dunbar, & McClelland, 1990), distractor words in the response set interfere more with performance in the Stroop (Proctor, 1978) and PWI tasks (Lupker &

Katz, 1981) than distractor words that are not also targets. Although the effect of set overlap is contested (Caramazza & Costa, 2000), it seems to be especially large (or at least more reliable) when set size is small (Roelofs, 2001), as is commonly the case in Stroop experiments (e.g., Fagot & Pashler, 1992). Furthermore, the presence of congruent trials, in which the distractor word matches the target word, tends to increase interference effects (Lowe & Mitterer, 1982).

Third, the response set in the Stroop task consisted of words belonging to a single category – colors – whereas picture names in the PWI task belonged to a variety of categories. The contrast between these is akin to the difference between the semantically homogeneous and heterogeneous conditions in a semantic blocking experiment (e.g., Damian, Vigliocco, & Levelt, 2001), in which interference accumulates more rapidly in repeated groups of pictures when they share a semantic category.

Some of these methodological differences (overlap of response and distractor sets, presence of congruent trials, fewer semantic categories) may be able to explain why Stroop interference persisted in the short SOA condition (Fagot & Pashler, 1992), but semantic PWI interference did not (Dell'Acqua, Job et al., 2007). Other differences (size of response set, degree of repetition) may be inconsistent with such an account. It would be difficult to speculate whether, as a whole, these differences can account for the divergent results.

Fortunately, such speculation is unnecessary, as the question can be addressed empirically. Piai et al. (2012), in an unsuccessful attempt to reproduce the results of Dell'Acqua, Job et al. (2007) in Dutch, conducted six dual-task semantic PWI experiments. In every experiment, participants were presented with a tone and a picture-word stimulus, and had to perform tone discrimination before picture naming. Five of the experiments (1–5) used a short SOA condition of 0 ms, at which the tone, picture and word stimuli were presented simultaneously. Of these, four experiments (2–5) used 32 pictures that belonged to eight different semantic categories with four objects per category. Semantically related distractors were created by pairing each picture with the name of another same-category picture, and unrelated distractors were created by pairing pictures with distractors from another category; thus, the distractor set matched the response set. (Experiment 2 also contained congruent distractors.) Depending on the experiment, pictures were repeated between 5 and 12 times. Across these four experiments, semantic PWI effects at the 0 ms SOA ranged from 27 ms to 51 ms, with an average of 36 ms.

The other experiment that used a 0 ms SOA condition, Experiment 1, was designed to directly compare performance in the Stroop and semantic PWI tasks. As such, Piai et al. (2012) restricted the PWI block to three pictures, all from the same semantic category. Distractors were either congruent (the name of the presented picture), semantically related (the name of a different picture), or a string of Xs. Pictures were repeated 72 times each. At the 0 ms SOA, pictures were named 80 ms slower when paired with incongruent distractors relative to congruent distractors (and 92 ms slower than the string of Xs). Thus, a semantic PWI task with the design of a standard Stroop task showed more than twice as much interference as experiments with a larger response set, fewer repetitions, no congruent trials, and more semantic categories.

Interestingly, the Stroop-like semantic PWI experiment showed more interference than the PWI-like PWI experiments even though some of the methodological differences between them, when considered in isolation, indicated that the reverse should be true. Either the differences that favored more interference for the Stroop-like design outweighed the others, or the identified differences may have interacted in some way. For example, a small distractor set that matches the response set and consists solely of same-category words,

combined with extreme repetition, may lead to activation saturation of the shared category node and target/distractor lemmas, thereby slowing the decay of distractor activation. At shorter task SOAs, when interference from written distractors in a standard PWI task would be decaying, this would prolong the interference from the words in the Stroop task (Fagot & Pashler, 1992) and the Stroop-like semantic PWI task (Piai et al., 2012; Experiment 1). Regardless of which methodological differences are ultimately responsible, however, the data from Piai and colleagues suggest that the contrast between the reliability of Stroop and semantic PWI effects at a short task SOA cannot be taken as evidence that the distractor word is processed differently in the two tasks.

Because the differential automaticity hypothesis claims that all kinds of PWI should be affected – not just manipulations of semantic relatedness – it is important to consider whether it can be squared with the results of other PRP studies. Several experiments have been conducted to determine whether Task 1 manipulations of phoneme selection propagate to Task 2 RTs, with mixed results (Cook & Meyer, 2008; Ferreira & Pashler, 2002, Experiment 2; Roelofs, 2008). However, only one paper has reversed the order of tasks to determine whether manipulations of Task 2 phoneme selection difficulty are absorbed into slack. In two experiments with Task 2 picture naming, Ayora et al. (2011) showed that pictures accompanied by simultaneously presented distractors were named faster at both short and long task SOAs when those distractors were phonologically related to picture names relative to when they were phonologically unrelated. If reducing task SOA caused the distractor words to be processed earlier relative to phoneme selection, that would be equivalent to reducing distractor SOA. However, single-task phonological PWI studies have found facilitation not just when words are presented simultaneously with or after pictures (e.g., Schriefers et al., 1990), but also at a –300 ms distractor SOA (Jescheniak & Schriefers, 2001, though distractor words were presented auditorily), and sometimes at a –150 ms distractor SOA (Jescheniak & Schriefers, 2001; but see Schriefers et al., 1990). This means that if a task SOA of 100 ms causes the distractor word to be processed (e.g.) 300 ms earlier relative to phoneme selection than at a 1000 ms task SOA, facilitation should still be observed. Thus, these data are consistent with the differential automaticity hypothesis.

Why do simultaneously presented distractors only sometimes show semantic interference at short task SOAs?

In attempting to figure out why they observed a semantic interference effect in the 100/0 condition when Dell'Acqua, Job et al. (2007) and Ayora et al. (2011) did not, Schnur and Martin (2012) suggested that individual differences concerning the difficulty of Task 1 might be at work. When they analyzed the data from nine participants whom they excluded for committing more than 20% errors in the tone task, they found a semantic interference effect of –45 ms in the 100/0 condition (as compared with 25 ms of interference among non-excluded participants). This is consistent with an account in which participants strategically postpone Task 2 processing after response selection when Task 1 is difficult in order to avoid completing Task 2 before Task 1, causing Task 2 response selection to be absorbed into slack (e.g., Meyer & Kieras, 1997). However, the data from Experiment 1 do not support this hypothesis. Across the six participants who were excluded for committing more than 20% errors in the tone task, the semantic interference effects when distractors were presented simultaneously were 18, 21 and 64 ms for the 100, 350 and 1000 ms task SOA conditions, respectively (compared with 18, 28 and 35 ms among participants who were included in the analysis). In particular, the interference effect in the 100/0 condition was exactly the same magnitude for the two groups.

As difficulty can be reflected in reaction times as well as error rates, such an account might also predict that participants who responded to tones more slowly at short task SOAs should show smaller semantic interference effects at those same SOAs. For each of the 41

participants included in the analysis, the average RT1 for the 100/0 condition (collapsing across distractor relatedness) was correlated with the size of the semantic interference effect on RT2 in the 100/0 condition. There was no relationship between these variables ($p = .95$), indicating a lack of support for the hypothesis that Task 1 difficulty determines the (dis)appearance of semantic interference.

If Task 1 difficulty cannot explain the unstable nature of semantic PWI in the 100/0 condition, what can? One possibility hinges on individual differences in word reading skill. Evidence from dual-task studies with Task 2 single word naming (Ruthruff et al., 2008) and lexical decision (Lien et al., 2006) indicates that reliance on central attentional resources during word reading may decrease as reading skill increases. Applied to the experiments at hand, skilled readers should show less semantic interference in the 100/0 condition than less skilled readers, since the ability to read words while central resources are engaged elsewhere is precisely what leads to the temporal separation of word and picture processing at short task SOAs. However, without any evidence that the participants tested by Dell'Acqua, Job et al. (2007) and Ayora et al. (2011) were more skilled readers than those tested by Schnur and Martin (2012) and Piai et al. (2012), this account is unable to explain the differences observed between experiments.

Another, more likely possibility is that the phonological regularity of written distractor words may play an important role in determining when the effect appears. In the Dual Route Cascaded model of visual word recognition and reading aloud (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001), when a printed word is to be read aloud, its phonological code – that is, the set of phonemes that constitute its pronunciation – is generated simultaneously via two routes. One, the lexical route, essentially performs a dictionary lookup, correctly retrieving the phonology of the written word and feeding activation in turn to the phoneme system. The other, the sub-lexical route, generates a phonological code through the use of language-specific rules governing the mapping of graphemes to phonemes. The sub-lexical route is the only one that will generate a code for nonwords and novel words because the language system cannot retrieve a stored code for a letter string it has never seen. However, it will generate an incorrect code for a phonologically irregular word that does not follow the normal pronunciation rules; e.g., it will generate a pronunciation for “pint” that rhymes with “mint”.

When they proposed the logic underlying the differential automaticity hypothesis, Besner et al. (2009) investigated the attentional demands of reading phonologically regular and irregular words aloud in a dual-task experiment. They concluded that phonological code retrieval via the lexical route could occur simultaneously with central resource-demanding Task 1 tone processing, but that phonological code generation via the sub-lexical route required central resources and thus was delayed by the central bottleneck.

This distinction may be relevant to the question of why semantic interference has sometimes been observed at short task SOAs, including the 100/0 condition, in English (Schnur & Martin, 2012) and Dutch (Piai & Roelofs, 2013; Piai et al., 2012; but see van Maanen et al., 2012), but not in Italian (Ayora et al., 2011; Dell'Acqua, Job et al., 2007). Italian has a relatively shallow orthography, as the correct sequence of phonemes for any Italian word can be derived from its spelling (Lepschy & Lepschy, 1991). Thus, the phonological codes generated by the lexical route and the sub-lexical route will be identical. In contrast, English has a deep orthography and contains many phonologically irregular words with exceptional spelling-to-sound mappings, and Dutch falls between Italian and English on the orthographic depth spectrum (Seymour, Aro, & Erskine, 2003). Thus, in these two languages, the phonological codes generated by the two routes will sometimes conflict.

Although the picture-word interference task used in Experiment 1 did not require participants to read distractor words aloud, it is likely that participants still generated those words' phonological codes. Evidence for this comes from the facilitative effects of phonologically related distractors (e.g., Schriefers et al., 1990), as well as from a variety of other psycholinguistic paradigms (see Frost, 1998 for a review). Because the phonological codes generated by the lexical and sub-lexical routes for irregular English distractor words conflict, interference between the two codes should prolong distractor processing, reducing the effects of distractor decay in the 100/0 condition and leading to the emergence of semantic interference.⁴ Alternatively, the code generated by the sub-lexical route might simply refresh the activation of the distractor lemma more when it conflicts with the code generated by the lexical route. Either way, because these codes do not conflict for regular distractor words – a set that includes every written distractor in Italian – distractor decay would proceed as normal in the 100/0 condition, leading to the disappearance of semantic interference.

If this is correct, any evidence for a potential effect of semantic relatedness in the 100/0 condition should have come exclusively from trials on which related distractors were phonologically irregular. In contrast, trials with phonologically regular related distractors should more closely replicate the results of Dell'Acqua, Job et al. (2007). To test this hypothesis, the regularity of the distractors used in Experiment 1 was computed using the Dual Route Cascaded model's GPC Strength Calculator (Coltheart et al., 2001). Grapheme-phoneme correspondences, a continuous measure of phonological regularity, were computed independent of rule position, using mean summed frequency. A median split on these correspondences was performed within each level of distractor relatedness (related and unrelated), and participant means were computed separately for each level of regularity.⁵

The results are presented in Table 1. On trials with phonologically regular distractors, PWI decreased for simultaneously presented distractors by 15 ms and increased for delayed distractors by 26 ms as task overlap increased – the same overall pattern observed in Experiment 1. In addition, the effect of semantic relatedness was much smaller on trials with regular distractors: In the critical 100/0 condition, PWI shrank to 5 ms, as compared with a 51 ms effect on trials with irregular distractors. The same patterns, only more pronounced, were present in the item (distractor) means: PWI decreased for simultaneously presented, regular distractors by 23 ms and increased for delayed, regular distractors by 50 ms. Furthermore, the PWI effect in the 100/0 condition was –9 ms for regular distractors as compared with 56 ms for irregular distractors.

Two conclusions can be drawn from these analyses. First, there was a near-total absence of semantic interference in the 100/0 condition on trials with phonologically regular distractors, which contrasted with robust interference generated in the same condition by phonologically irregular distractors. Given that all Italian words, but not all English or Dutch words, are phonologically regular, this result can accommodate both the consistent lack of semantic interference in the 100/0 condition observed by Dell'Acqua and colleagues in Italian (Ayora et al., 2011; Dell'Acqua, Job et al., 2007) and the inconsistent effects of semantic interference in both English (Schnur & Martin, 2012; Experiment 1 of this paper) and Dutch (Piai & Roelofs, 2013; Piai et al., 2012; van Maanen et al., 2012). Second, an increase in

⁴Though Besner et al. (2009) found that the effect of phonological regularity on reading aloud time at a short task SOA was eliminated, participants still made more errors at that SOA when reading irregular words than regular words. This increased difficulty is consistent with the present account.

⁵The 27 distractors in each relatedness condition were split into two groups of 13. The median distractors, *plum* (related) and *needle* (unrelated), were excluded because they were associated with relatively extreme naming latencies and there was no principled method of determining whether they should group with more regular or less regular distractors. However, grouping them with more regular distractors disrupted the monotonic PWI trend in the delayed distractor condition reported here.

semantic interference for delayed distractors as task overlap increased was observed for phonologically regular distractors. This is important because it indicates that the differential automaticity hypothesis can explain the absence of interference in the 100/0 condition precisely under those conditions that fail to elicit it – namely, when distractors are phonologically regular.

In contrast to its effects on semantic PWI, the effect of phonological regularity on Stroop interference in dual-task settings is likely to be more limited. All else being equal, phonologically irregular color words should show more interference at short task SOAs than phonologically regular color words. However, with the methodological differences between Stroop and PWI experiments interacting to prolong Stroop interference, distractor activation would likely persist across Task 2 cognitive slack regardless of phonological regularity.

Conclusions

Picture-word interference, especially when used in a dual-task paradigm, is a complex task. In the context of the central bottleneck model and PRP logic, it is tempting to assume that each task consists of a single perceptual encoding stage, a single response selection stage, and a single response execution stage. However, such an assumption suffers from oversimplification (potentially like the central bottleneck model itself; cf. Magen & Cohen, 2010; Meyer & Kieras, 1997; Roelofs & Piai, 2011; Tombu & Jolicoeur, 2003). As the task name suggests, picture-word interference results from the conflict between the processing of two stimuli – a picture and a word – that have different attentional demands. Picture naming processes at least as early as lemma selection require central attentional resources. In contrast, words can activate their corresponding lemmas without relying on central resources (Reynolds & Besner, 2006), though the generation of phonological codes itself consists of two subprocesses, one of which requires central resources (generation via the sub-lexical route) and one of which does not (generation via the lexical route; Besner et al., 2009). Furthermore, due to differences in orthographic depth, distractor processing may not behave the same way in every language. It is only by taking these complexities into account that accurate inferences may be drawn about the locus of interference generated by words in dual-task experiments.

Though theoretical disagreements remain over how speakers are able to select words from a large set of potential responses with almost ruthless efficiency, there is no longer any reason to think that semantic PWI is resolved prior to that selection process. Given this, the results of Dell'Acqua, Job et al. (2007) and Ayora et al. (2011) do not, in the end, present a challenge for major models of word production (Levelt et al., 1999), PWI (Mahon et al., 2007), or the Stroop task (Cohen et al., 1990; Roelofs, 2003).

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Appendix. Critical Pictures Used in Experiment 2

Audio-visual: headphones, microphone, radio, speaker, television

Body parts: ear, eye, finger, hand, nose

Buildings: castle, church, house, lighthouse, windmill

Celestial phenomena: cloud, lightning, moon, rainbow, star

Clothes: glove, jacket, pants, skirt, sock

Farm animals: cow, donkey, horse, pig, sheep

Furniture: bed, chair, desk, stool, table

House parts: balcony, chimney, door, roof, window

Musical instruments: drum, guitar, piano, trumpet, violin

Tableware: cup, fork, glass, knife, spoon

Tools: ax, drill, hammer, saw, screwdriver

Transport: bus, car, helicopter, plane, truck

Figure 1.

The central processing bottleneck in the dual-task paradigm. PE = perceptual encoding (beginning immediately after stimulus presentation), RS = response selection, and RE = response execution (after which a response is issued); SOA = stimulus onset asynchrony. RT1 and RT2 represent reaction times to each task. White boxes denote processing stages that do not require domain-general attentional resources; black boxes denote processing stages that do.

Figure 2.

Dell'Acqua et al.'s (2007) account of picture-word interference (PWI) in a dual-task paradigm. Task 1 = tone discrimination; Task 2 = picture naming. PE = perceptual encoding; RS = response selection; RE = response execution; SOA = stimulus onset asynchrony; PWI = picture-word interference. Under Dell'Acqua et al.'s account, semantically related distractor words generate PWI at every task SOA. (a) When the picture-word stimulus is presented at a long delay after the tone, this PWI increases picture naming latencies. (b) When the picture-word stimulus is presented soon after the tone, PWI resolution is absorbed into the "cognitive slack" created by the bottleneck, yielding no effect of distractor relatedness.

Figure 3.

Logic of Experiment 1 for trials with semantically related distractor words. Task 1 = tone discrimination; Task 2 = picture naming. PE = perceptual encoding; RS = response selection; RE = response execution; SOA = stimulus onset asynchrony; PWI = picture-word interference. (a) When the word and picture are presented simultaneously, PWI emerges at a long task SOA due to the temporal proximity of word processing to lemma selection. Reducing the delay between tone and picture temporally separates word processing (which does not require central attentional resources) and lemma selection (which does), causing PWI to diminish. (b) When the word is presented after the picture, no PWI is generated at a long task SOA because the word is processed too late to interfere with lemma selection. However, reducing the delay between the tone and picture causes the long distractor SOA and short task SOA to cancel out: Word processing re-synchronizes with lemma selection, leading to the emergence of PWI.

Figure 4.

Experiment 1 tone discrimination (Task 1) and picture naming (Task 2) latencies shown as a function of task stimulus onset asynchrony (SOA), distractor SOA, and distractor relatedness. Error bars for each task represent 95% confidence interval halfwidths; pairwise differences between condition means that exceed error bar length are statistically significant.

Figure 5.

Experiment 2 tone discrimination (Task 1) and picture naming (Task 2) latencies shown as a function of task stimulus onset asynchrony (SOA) and ordinal position. Linear effects of ordinal position on reaction times are denoted by best-fit lines. Error bars for each task represent 95% confidence interval halfwidths; pairwise differences between condition means that exceed error bar length are statistically significant.

Table 1

Semantic Picture-Word Interference Effects in Experiment 1 by Task SOA, Distractor SOA, and Distractor Phonological Regularity

Distractor regularity and distractor SOA	Task SOA		
	100 ms	350 ms	1000 ms
Regular			
0 ms	5	16	20
250 ms	15	11	–11
Irregular			
0 ms	51	52	62
250 ms	52	20	14

Note. SOA = stimulus onset asynchrony; ms = milliseconds. Phonological regularity of distractors was determined by a median split on grapheme-phoneme correspondence within each level of distractor relatedness (see text for details).