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The role of domain-general frontal systems in language comprehension: Evidence from dual-task interference and semantic ambiguity

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ABSTRACT

Neuroimaging studies have shown that the left inferior frontal gyrus (LIFG) plays a critical role in semantic and syntactic aspects of speech comprehension. It appears to be recruited when listeners are required to select the appropriate meaning or syntactic role for words within a sentence. However, this region is also recruited during tasks not involving sentence materials, suggesting that the systems involved in processing ambiguous words within sentences are also recruited for more domain-general tasks that involve the selection of task-relevant information. We use a novel dual-task methodology to assess whether the *cognitive* system(s) that are engaged in selecting word meanings are also involved in non-sentential tasks. In Experiment 1, listeners were slower to decide whether a visually presented letter is in upper or lower case when the sentence that they are simultaneously listening to contains words with multiple meanings (homophones), compared to closely matched sentences without homophones. Experiment 2 indicates that this interference effect is not tied to the occurrence of the homophone itself, but rather occurs when listeners must reinterpret a sentence that was initially misparsed. These results suggest some overlap between the cognitive system involved in semantic disambiguation and the domain-general process of response selection required for the case-judgement task. This cognitive overlap may reflect neural overlap in the networks supporting these processes, and is consistent with the proposal that domain-general selection processes in inferior frontal regions are critical for language comprehension.

1. Introduction

Speech comprehension depends on computations by which our stored knowledge about single words is combined into a higher-order representation of the meaning of an entire utterance. This combination process involves far more than simple summation of the meanings of the individual words. For each word in a sentence, the listener must use the surrounding words to guide the selection of the appropriate syntactic role and semantic properties of that word. For example, in the phrase "the bark of the dog", the syntactic properties of the word "the" indicates that "bark" is being used as a noun and not a verb, while the semantic properties of the word "dog" indicate that "bark" is referring to the noise made by that animal and not the outer covering of a tree. How these combinatorial aspects of speech comprehension are organised within the brain remains a key issue in cognitive neuroscience.

Evidence suggests that the left inferior frontal gyrus (LIFG) plays a critical role in language-relevant combinatorial processes. Historically there has been a close association between the LIFG and syntactic processing. This association was largely based on evidence that so-called 'Broca's aphasics' have difficulties processing sentences in which syntax cues must be accurately processed for the sentence to be correctly understood. For example, when such patients are presented with sentences like "the cat that the dog is chasing is brown" they have difficulty in using syntactic cues to determine that (1) it is the dog that is chasing the cat, and (2) it is the cat that is brown (e.g., Caramazza & Zurif, 1976). Although more recent neuropsychological findings have called into question the specific association between LIFG damage and syntactic processing deficits (Dronkers, Wilkins, Van Valin, Redfern, & Jaeger, 2004), this association is still present in some accounts of language processing (e.g., Grodzinsky & Santi, 2008) and is supported by a large collection of neuroimaging studies show increased activation in this region for sentences that are more syntactically complex (see Dapretto and Bookheimer (1999), Grodzinsky and Amunts (2006), and Kaan and Swaab (2002) for detailed reviews and historical perspectives). On the other hand, several lines of evidence indicate that the role of LIFG is not restricted to processing syntactic aspects of language, but is also involved in semantic aspects of sentence comprehension. EEG studies have shown that the online

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processing of semantic ambiguities is impaired in 'Broca's aphasics', in particular that the suppression (or decay) of the inappropriate meanings of an ambiguous word is delayed in these patients (Swaab, Brown, & Hagoort, 1998). In addition, a number of imaging studies have shown LIFG activation in response to semantic ambiguity. For example, Rodd, Davis, and Johnsrude (2005) showed that spoken sentences containing homophones[1] (e.g., "the pitch of the note was extremely high") produced increased fMRI BOLD signal in the LIFG compared with well-matched control sentences. Similar results have been observed in studies of sentence reading (Mason & Just, 2007; Zempleni, Renken, Hoeks, Hoogduin, & Stowe, 2007). Finally, a recent fMRI study demonstrates overlapping clusters of activity in the LIFG are produced by both semantic and syntactic ambiguities within the same participants (Rodd, Longe, Randall, & Tyler, 2010). These studies suggest that the LIFG might contribute more generally to combinatorial aspects of language comprehension (Hagoort, 2005; Rodd et al., 2005; Willems & Hagoort, 2009).

In addition to these studies of language comprehension, neuroimaging studies reveal LIFG activation for a diverse set of cognitive demands in experiments that involve both linguistic and non-linguistic stimuli (see Duncan & Owen, 2000). Partly in response to this evidence, Thompson-Schill and colleagues (January, Trueswell, & Thompson-Schill, 2008; Novick, Trueswell, & Thompson-Schill, 2005) proposed that overlapping neural systems are recruited for high-level (syntactic and semantic) aspects of sentence comprehension and for a range of other non-linguistic processes that involve selection of task-relevant information from competing alternatives (Moss et al., 2005; Thompson-Schill, D'Esposito, Aguirre, & Farah, 1997). These accounts contrast with theories in which the LIFG plays a highly specialised role in linguistic processing (e.g., Grodzinsky, 2000; Grodzinsky & Santi, 2008). The proposal that high-level aspects of sentence comprehension are being performed by domain-general systems also runs counter to the influential view that sentence processing is a highly specialised cognitive task, performed by dedicated domain-specific modules (Fodor, 1983). However, the overlap apparent in fMRI activations for linguistic and non-linguistic tasks does not rule out the possibility that linguistic and non-linguistic functions are supported by adjacent but separable sub-systems within the LIFG or even that this single anatomical region may support multiple cognitive functions in intertwined, but functionally distinct networks. Neuroimaging evidence alone provides insufficient functional and anatomical resolution to rule out these alternative explanations.

The experiments reported here provide behavioural evidence that the *cognitive* processes that are engaged for high-level aspects of sentence comprehension are also involved in a non-sentential task that requires domain-general selection processes. We use a dual-task method to measure the extent to which an increase in the difficulty of sentence processing (due to the presence of semantically ambiguous homophones (e.g., "bark" and "knight/night") has consequences for listeners' ability to perform a non-sentential secondary task. This approach relies on the assumption that interference between two tasks indicates that they share a common cognitive resource (Pashler, 1994; Tombu & Jolicoeur, 2003). If performance on the secondary task is affected by the presence of a concurrent semantic ambiguity, then this would provide evidence for a common domain-general functional system involved in both tasks.

[1] The term homophone refers to cases where a single phonological form corresponds to multiple word meanings. This includes homonyms, which also share their orthographic form (e.g., bark, bank), as well as homophones that have different spellings (e.g., knight/night, leek/leak). In some cases the different meanings are etymologically related and so would be considered by some to be multiple senses of a polysemous word rather than a true homonym.

In the current experiments, participants listen to sentences that contain homophones. At the offset of each sentence, they perform a semantic-relatedness judgement on a visually presented single word to ensure comprehension. In addition, at some point during the sentence, a single letter is displayed and listeners must decide whether the letter is in upper or lower case. This case-judgement task was selected as our non-sentential secondary task for several reasons. First, a choice RT task is required so that participants need to select an appropriate response from the (two) possible options. This choice element of the task is important for our assumption that the task will recruit frontal selection areas (Duncan & Owen, 2000). In addition, this task is unlikely to cause any perceptual or linguistic interference, and it is sufficiently easy for participants to perform well under these relatively demanding dual-task conditions. It is also advantageous that the two response categories ('upper case' and 'lower case') are sufficiently well-established that no pre-experimental training is needed, and that any competition effect can confidently be ascribed to the competition between the two possible responses and not to the need to maintain newly created response categories in mind. Finally, to ensure that response-selection processes are necessarily engaged, it was desirable to use a task that cannot be performed on the basis of any one perceptual feature and where the stimulus–response mapping is completely arbitrary (i.e. based on previously instructed rules and not on the intrinsic characteristics of the stimuli, cf. Simon, 1969).

The critical question under test is whether performance on this case-judgement task is modulated by the presence of semantic ambiguity in the sentence to which listeners are simultaneously attending. The two experiments presented here: (1) provide evidence for such an interference effect and (2) isolate a specific linguistic process that best explains the observed interference effect.

2. Experiment 1

2.1. Method

2.1.1. Participants

The participants in both experiments were right-handed and aged 18–40, had English as their first language and had normal (or corrected-to-normal) vision. Thirty-three participants were tested in Experiment 1.

2.1.2. Stimuli

We used 59 high-ambiguity (HA) and 59 low-ambiguity (LA) control sentences (as in Rodd et al. (2005)). Each HA sentence contained at least two homophones (e.g., "there were <u>dates</u> and <u>pears</u> in the fruit bowl"). The sentences were relatively short (mean number of words = 9.3) and the few words that occurred before the first homophone (mean = 1.4) in the sentence were never sufficient to indicate which meaning was correct (e.g., "The pitch...", "There were currents/currants..."). In many cases the second homophone that served to disambiguate the first homophone (e.g., "she <u>filed</u> her <u>nails</u> before she polished them"). The homophones included words where the two meanings correspond to the same spelling (e.g., dates), as well as those that did not (e.g., pairs/pears). This increased the pool of potential stimuli and allowed the construction of sentences that contained a considerable degree of ambiguity while sounding highly natural as confirmed by subjective ratings (see Rodd et al., 2005). Each HA sentence was matched with a LA sentence (e.g., "there was beer and cider on the kitchen shelf") for number of syllables and words, syntactic structure, duration, frequency of the content words and ratings of naturalness and imageability (see Rodd et al., 2005).

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For the case-judgement task, each sentence was pseudorandomly assigned a single letter from the set ABDEFGHNQRT (avoiding letters with similar upper/lower form, e.g., o/O). Each HA sentence was assigned the same letter as its LA control sentence. Two versions of the experiment were created, such that, for each sentence, half the participants viewed the upper-case version of the letter and half the lower-case version. In each version half of the letters were presented in lower case, and half in upper case.

For each sentence a word was selected for use in the semantic-relatedness task. These words were either strongly related (50%) or unrelated (50%) to the sentence's meaning (e.g., "the seal came up onto the bank of the river, SHORE" vs. "the match ended as a tie, CLIMATE"). This task was designed to be relatively easy and was included solely to ensure that participants attended to the meaning of the sentences. These target words were matched between conditions for length, frequency and semantic relatedness (see Rodd et al., 2005), and were not related to an unintended meaning of the homophones.

2.1.3. Procedure

Participants were tested in a quiet room while wearing headphones. The experiment was presented using DMDX (Forster & Forster, 2003). Trials started with an auditory sentence. At the offset of the second homophone in this sentence (or the corresponding unambiguous word in the LA sentences) the target letter was presented. It is at this point in the sentence that the processing impact of the two homophones is likely to be maximal. These offset locations were manually identified by one of the authors (JR). Participants responded via a button box by using the index finger of their dominant hand for upper-case letters and the index finger of their non-dominant hand for lower-case letters. The target letter remained on the screen until the participant responded (timeout = 1000 ms). At the sentence offset or after they had responded to the letter (whichever was later), the probe word for the semantic-relatedness judgement appeared on the screen. Participants responded 'related' with the index finger of their dominant hand and 'unrelated' with the index finger of their non-dominant hand. The next trial began after a 1000 ms delay. A practice block (14 sentences) was followed by 118 experimental items, pseudorandomly assigned to four blocks each starting with three filler items and followed by a short break. Sentences in each block were randomly ordered for each participant.

2.2. Results and discussion

2.2.1. Semantic-relatedness task

The participants' mean error rate was 6% (range: 0–17%). This confirms that they were attending to each sentence's meaning. These responses were not analysed further as this task was included solely to ensure attention to the sentences.

2.2.2. Case-judgements

The mean error rate was 6% (range: 0–26%). Mean response times and error rates were calculated separately across items and participants, and were submitted to separate repeated-measures ANOVAs (see Table 1). Version was included as a dummy variable in all analyses, but main effects and interactions involving version are not reported (Pollatsek & Well, 1995). Responses were significantly slower during HA than LA sentences ($F_1(1, 31) = 7.2$, $p < .05$; $F_2(1, 57) = 8.0$, $p < .01$). Responses were slower for lower-case items than for upper-case items ($F_1(1, 31) = 14.3$, $p < .001$; $F_2(1, 57) = 40.7$, $p < .001$), probably due to the use of participant's dominant hand for upper case responses. The interaction between ambiguity and case was also non-significant (both $F < 1$). Analyses of the error rates showed no significant main effects of ambiguity or case, or interaction between these variables (all $F < 1$).

Experiment 1 demonstrates that case-judgements were significantly slowed when participants listened to sentences containing homophones, compared to matched sentences without homophones. This suggests that some cognitive process involved in resolving the meaning of the homophones in the HA sentences is also involved in case-judgement. Such an interference effect is consistent with a single, common neural system contributing both to ambiguity resolution and to the response selection component of this choice RT task.

Table 1
Experiment 1: Mean response times and error rates (from items analyses).

Sentence condition	Case	Response times (ms)		Percent error	
		Mean	Std. dev.	Mean	Std. dev.
High-ambiguity	Upper	529.9	40.6	6.8	6.6
High-ambiguity	Lower	560.5	49.0	6.5	5.8
Low-ambiguity	Upper	520.4	49.8	5.4	6.1
Low-ambiguity	Lower	545.9	49.8	6.7	6.1

3. Experiment 2

The results of Experiment 1 provide evidence that some aspect of the comprehension of high-ambiguity sentences involves a domain-general cognitive system. However, ambiguity resolution involves multiple component processes and it is unclear which of these may be responsible for the interference effect. Most current accounts of ambiguity resolution (see Twilley and Dixon (2000) for review) can be characterised as exhaustive access models in which multiple meanings are initially activated in parallel and where the degree of this activation is influenced by both the relative frequencies of the different meanings and the extent to which they are consistent with the preceding context. This activation process is then followed by rapid selection of a single meaning dependent on sentence context and relative meaning frequency. For sentences in which the initially selected meaning turns out to be incorrect, later reanalysis may be required. Thus the high-ambiguity sentences in Experiment 1 are likely to increase the load on three different component processes involved in: (i) initially activating multiple word meanings, (ii) selecting between these meanings, and (iii) reinterpreting sentences that are initially misparsed. The aim of Experiment 2 is to determine which of these cognitive processes interferes with the case-judgement task by using sentences that contain homophones, yet place different loads on these three aspects of disambiguation. Each high-ambiguity sentence will contain one homophone which will be disambiguated by a word that occurs either before the homophone, immediately after the homophone, or towards the end of the sentence. We predict that activation of multiple word meanings will only occur at the time that the homophone is presented, whereas meaning selection can also occur later in the sentence when disambiguating information if available. Reinterpretation is only likely if sufficient time elapses between the ambiguous word and disambiguation for incorrect meaning selection to have previously occurred. By presenting the case-judgement probe at one of three different time points within each sentence and comparing latencies with responses following matched sentences without homophones, we can assess whether the interference effect is time-locked to the presentation of the homophone itself or the disambiguating word(s).

A range of different outcomes is possible. First, interference may be observed whenever the homophone is presented but be absent later in the sentence. This would suggest that interference is primarily associated with the initial activation of the word meanings. Second, if interference is primarily associated with meaning selection then it will be observed for all sentence types but may be

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Table 2
Experiment 2: Example sentences (homophone in bold, disambiguation region in italics). Numbers indicate cue positions used in word-completion test and experiment.

Condition	Example sentence
Prior	The *hunter* thought that the **hare** (1) in the field (2) was actually a rabbit (3)
Immediate	The scientist thought that the **film** (1) on the *water* (2) was from the pollution (3)
Delayed	The ecologist thought that the **plant** (1) by the river (2) should be *closed down* (3)
Control	The hikers believed that the hill (1) in the distance (2) was not very big (3)

present both at the time of the homophone itself as well as at any subsequent disambiguating context. Third, if interference is only seen when listeners are required to reinterpret a sentence that was initially misparsed then it should only occur late in the sentence and should be limited to those sentences that were not disambiguated by prior context. Finally, the observed results may reflect some combination of these possible outcomes, suggesting that interference is not restricted to a single aspect of disambiguation.

3.1. Stimuli

Three sets of high-ambiguity sentences, all containing one homophone, were used together with one set of low-ambiguity control sentences (Table 2). In the 'prior' condition, the homophone is disambiguated by the preceding context. In the 'immediate' condition, disambiguation occurs a few words (1–4) after the homophone. In the 'delayed' condition, disambiguation is delayed until later in the sentence (5–16 words after the homophone). For the 'immediate' sentences the offset of the disambiguating word came, on average, 0.7 s after the offset of the ambiguous word. For the 'delayed' sentences this delay was 2.4 s. The sentences were constructed in quartets (one from each condition) such that sentences in each quartet had similar syntactic structures, duration, number of words, number of syllables, and position of the homophone (Table 3). There were 49 quartets (196 sentences). Three cue positions were manually located within the sound file for each sentence (Table 2): (1) the offset of the homophone (or the corresponding word in control sentences); (2) the offset of the word that disambiguates the 'immediate' sentences (or the corresponding word in the other sentences); and (3) the offset of the word that disambiguated the 'delayed' sentences (or corresponding word in the other sentences).

Semantic-relatedness judgement words and case-judgement letters were assigned as in Experiment 1, except that each sentence was always presented together with the same upper or lower case letter. The target letter for the case-judgement task was presented at one of the three cue positions described previously. To ensure that participants only heard each sentence once, three versions of the experiment were created. All sentences were presented in each version, but the cue position at which the case-judgement task appeared differed across versions. Within each version, the case-judgement task was presented at the same cue position for all sentences from a particular quartet. Each sentence was paired with the same letter and semantic-relatedness judgement probe word in all versions of the experiment.

3.2. Sentence-completion pre-tests

To confirm that the homophones were disambiguated as intended, we conducted two separate sentence-completion pre-tests. In Pre-test 1, 13 volunteers (who did not participate in the experiment) heard the initial part of the sentences from all three ambiguous conditions, but which had been cut off at cue position 1 (see above) and were instructed to write down an appropriate sentence ending. In Pre-test 2, 14 different volunteers listened to sentences from the immediate- and delayed-disambiguation conditions, which were cut off at cue position 2. Responses were coded according to whether they were consistent with the intended meaning. Responses that did not clearly differentiate between the two interpretations were discarded. Additional volunteers were then tested on subsets of the original items until at least 10 clear responses had been obtained for each item.

For the prior condition, 96% of responses at cue position 1 were consistent with the intended meaning, indicating successful disambiguation of the homophones. In contrast, results for the immediate and delayed conditions at this position (29% and 30% concordance with the intended meaning, respectively) indicate similar overall preferences for the non-intended interpretation. At cue position 2 the immediate sentences have been disambiguated (99% concordance), while the delayed sentences remain ambiguous (33% concordance). In summary, the pre-tests confirm that the sentences are being consistently disambiguated in the appropriate portion of the sentences.

3.3. Procedure

Forty-seven participants were pseudorandomly assigned to one of the three versions of the experiment. The procedure was similar to Experiment 1, except that the letter target for the case-judgement task was presented at one of the three cue positions described previously. In addition, to reduce case-judgement response times (and variability in response times, potentially increasing sensitivity), letter presentation time was reduced to 100 ms. A practice block of 20 sentences was followed by the experimental items, divided into 4 blocks of 49 test sentences (one sentence from each quartet presented in random order). Each block began with five filler sentences.

3.4. Results

3.4.1. Semantic-relatedness task

Two participants with error rates greater than 25% were excluded from all analyses. The remaining 45 participants (14, 15 and 16 participants in the three versions) had a mean error rate of 12% (range: 1–23%).

3.4.2. Case-judgements

The mean error rate was 5% (range: 1–14%). Mean response times and error rates (Fig. 1) were analysed as in Experiment 1

Table 3
Experiment 2: Descriptive statistics. Ambiguity position: number of words in the sentence that preceded the ambiguity. Disambiguation position: number of words between the ambiguity and disambiguation.

Condition	Duration (s)	Words	Syllables	Ambiguity position	Disambiguation position	Cue 1 position (s)	Cue 2 position (s)	Cue 3 position (s)
Prior	5.08	19.1	25.6	7.1		2.28	2.93	4.69
Immediate	5.12	19.1	25.2	7.0	1.7	2.27	2.95	4.72
Delayed	5.15	19.2	25.0	7.0	9.0	2.29	2.92	4.75
Control	4.93	19.1	25.5	7.0		2.16	2.80	4.52

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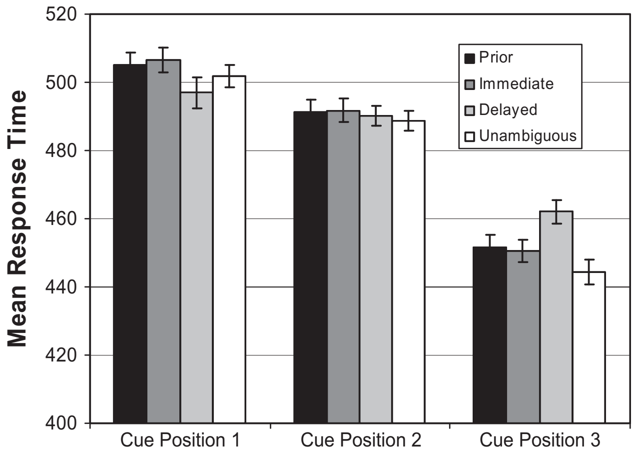

Fig. 1. Experiment 2: Mean response times in ms (from subjects analyses, error bars show std. error adjusted to remove between-subjects variance).

with the additional factor of cue position. To reduce the likelihood of a false positive in this $4 \times 3 \times 3 \times 2$ (sentence type $\times$ cue position $\times$ version $\times$ case) ANOVA all main effects and interaction involving case were ignored. This factor did not significantly interact with ambiguity in Experiment 1 and is of no theoretical interest. As with Experiment 1, effects involving version are also not reported. Responses showed a significant effect of cue position, with faster responses at later cue positions; $F_1(2, 84) = 152$, $p < .001$; $F_2(2, 86) = 103$, $p < .001$). The main effect of sentence condition was non-significant (both $p > .3$), but an interaction between condition and cue position was observed ($F_1(6, 252) = 2.3$, $p < .05$; $F_2(6, 258) = 2.6$, $p < .05$).

To explore the interaction between sentence condition and cue position, a separate repeated-measures ANOVA was conducted on the response time data at each of the three cue positions (with case, sentence type and version as factors). At cue positions 1 and 2 the main effect of sentence type was non-significant (all $p > .1$), whereas at cue position 3 the main effect of sentence type was significant ($F_1(3, 126) = 4.9$, $p < .01$; $F_2(3, 129) = 4.1$, $p < .01$). Post-hoc comparisons among the four conditions at cue position 3 (using Bonferroni correction) show that responses were significantly slower in the delayed-disambiguation condition compared to the low-ambiguity control condition (difference = 17 ms, both $p < .01$), and marginally slower in the delayed condition compared to the immediate and prior conditions ($p < .1$).

Analysis of the error rates showed a significant effect of cue position; more errors occurred at the earlier cue positions; $F_1(2, 84) = 10.5$, $p < .001$; $F_2(2, 86) = 14.1$, $p < .001$. The effect of sentence type and the interaction between sentence type and cue position were non-significant (both $p > .1$).

4. Discussion

In Experiments 1 and 2 listeners were slower to make concurrent case-judgements when they listened to sentences containing semantic ambiguities compared with matched low-ambiguity control sentences. This demonstrates that the increase in the cognitive processing load that is due to semantic ambiguity resolution directly affects participants' ability to perform an unrelated choice RT task.

All current accounts of dual-task interference propose that two tasks interfere with each other when both tasks load on a common system. In cases such as the present study, where there is no peripheral overlap between the two tasks, all accounts agree that dual-task interference arises from some central limitation. For example, in "bottle neck" accounts of task interference (e.g., Pashler, 1994) it is assumed that individual processors can only act on one input at a time and so when two tasks that both rely on a single processor are attempted, the second task must wait until the first is finished. In contrast, "capacity sharing" accounts (e.g., Tombu & Jolicoeur, 2003), assume that individual processors have limited capacity that can be divided between different tasks, such that two tasks can (under certain circumstances) be performed in parallel but that this will be less efficient that when one task is performed in isolation. While these two approaches clearly differ in terms of the mechanism by which multiple tasks are co-ordinated, they share the assumption that dual-task interference only arises whenever two tasks simultaneously place a load on a single shared processor. On the basis of this assumption, we focus our discussion on assessing the specific locus of the interference effect.

At face value, the main result may appear surprising. Case-judgement is a straightforward well-learned visual categorisation that requires neither perception of spoken stimuli nor lexical semantic processing. It is not immediately obvious that a case-judgement task should suffer specific interference from the presence of a homophone in a concurrently presented spoken sentence. The most likely explanation is that the response-selection element of the case-judgement task is competing for cognitive resources with semantic disambiguation. This view is consistent with the behavioural literature on dual-task performance, which emphasises the extent to which response-selection processes can create a critical central bottleneck (Pashler, 1994). It is also consistent with the cognitive neuroscience literature suggesting that response selection involves the same LIFG regions as semantic disambiguation.[2]

Experiment 2 was conducted to determine more precisely the aspect of ambiguity resolution that underlies the interference effect. In this experiment we used carefully constructed sentences in which the relative positions of a homophone and its disambiguating context were systematically varied. There was no significant impact on participants' case-judgement responses when disambiguation came either before or in the words immediately after the homophone, relative to control sentences. However, a significant dual-task interference effect was observed for sentences in which disambiguating information was presented late in the sentence, many words after the homophone (i.e., the delayed-disambiguation condition). To understand the implications of this finding, it is important to have a clear understanding of how listeners process these 'delayed' sentences. Most current models of ambiguity resolution (see Twilley and Dixon (2000) for review) suggest that, for sentences with this structure, listeners will make an early commitment to a single meaning and may then need to revise their initial interpretation when they encounter the disambiguating word. This view is supported by cross-modal semantic priming studies (e.g., Swinney, 1979) that suggest that listeners maintain both interpretations of a homophone for only a limited amount of time (perhaps as little as a second). For these 'delayed' sentences, the disambiguating information occurred on average 2.4 s after the ambiguity, making it highly likely that listeners will have already committed to a single interpretation before they encounter the disambiguating information, which will then trigger sentence reinterpretation. Thus, given that the interference effects only emerge right at the end of these 'delayed' sentences, it is likely that it is the reinterpretation element of disambiguation that is primarily responsible for

[2] Note that we cannot entirely rule out the possibility that the interference arises not because of the requirement to select the appropriate response (upper vs. lower case) but because of the requirement to select the correct task set (sentence comprehension vs. case judgement). This alternative explanation does not compromise our main conclusion – that the ambiguity resolution aspects of sentence comprehension rely on domain-general selection processes.

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the observed dual-task interference. Sentence reinterpretation is a complex cognitive operation that involves maintenance of material in working memory and processing of multiple constraints to select a new consistent interpretation of all the words that have been heard. These data suggest that some (or all) of these processes overlap with the domain-general response selection systems.

According to this view, it is may seem surprising that there was no comparable interference effect for the 'immediate' sentences. These sentences have a similar structure to the 'delayed' sentences, such that the ambiguity is resolved by a later disambiguation. The key difference between the conditions is that while the 'delayed' sentences have an average delay of 2.4 s between ambiguity and disambiguation, for the 'immediate sentences the delay was, on average, 700 ms. The absence of an interference effect for these 'immediate' sentences suggests that either (i) the cost of reinterpreting such a short section of the sentence is minimal, or more likely that (ii) listeners can maintain two meanings of a single word for this relatively short period of time and can thereby incorporate the disambiguating information into their initial selection decision and thereby avoid the need for reinterpretation.

The fact that the interference effect in Experiment 2 only emerges at the end of the sentence raises the possibility that it is due to the divided attention conditions eliciting a strategy (not used in normal comprehension) whereby listeners are delaying meaning selection until the end of the sentence. At face value this seems unlikely since it would place an additional heavy burden on working memory processes and would not therefore be a useful strategy for dual-task situations. Furthermore, data from cross-modal priming studies (e.g., Lucas, 1999; Swinney, 1979) is not consistent with this proposal. In these experiments, participants are in a similar dual-task situation – listening to an auditory sentence whilst waiting for a visual probe to arrive – and yet the results obtained under these conditions suggest that meaning selection occurs very rapidly after the offset of the ambiguous word.

In summary, the data from Experiment 2 suggest that the cognitive system involved in reinterpreting sentences that were initially misparsed, and the system subserving the response-selection aspects of the case-judgement task, have some element in common. The absence of interference effects for sentences in the prior or immediate disambiguation conditions might suggest that the cognitive processes associated with the initial activation or selection of word meanings does *not* substantially interfere with case-judgement. However, we should be cautious in drawing the conclusion that reinterpretation is the *only* aspect of ambiguity resolution that produces this interference effect. Although we did not observe an interference effect for 'immediate' disambiguation, we cannot rule out the possibility that such an effect might emerge using a more sensitive paradigm. Indeed the finding that 'Broca's aphasics' are impaired in their initial processing of ambiguous words (Swaab et al., 1998) is compatible with the idea that a frontal processing mechanism is also involved at an earlier stage. One hint that interference might arise in the absence of reinterpretation comes from Experiment 1, where the stimuli were not explicitly constructed to include delayed-disambiguation or reinterpretation, and where the interference effect was observed immediately after the offset of the second ambiguous word. Although the highly varied structures of these sentences makes it hard to draw definite conclusions about the critical cognitive process(es) that produce the interference effect, it is interesting to note that for some of these sentences the meanings of the ambiguous words were mutually constraining such that each homophone was disambiguated by the correct meaning of the other word. We estimate that approximately 54% of the sentences had this structure. It is therefore possible that the observed interference effect in Experiment 1 reflects (as in Experiment 2) reinterpretation, in this case driven by participants' need to reinterpret the meaning of the first ambiguous word as a consequence of the identity of the second ambiguous word. Alternatively, it is possible that the interference effect reflects the additional processing load due to the need to use mutual meaning constraints for two ambiguous words. This situation, in which a sentence contains multiple ambiguous words, is not well studied from a cognitive point of view and so at this time it is unclear whether the interference effect seen in Experiment 1 should be ascribed entirely to a need to reinterpret these sentences or whether the particularly challenging selection demands associated with these high-ambiguity sentences, containing multiple homophones, is the critical factor. Future work will assess whether this dual-task interference effect is restricted to processes of reinterpretation during ambiguity resolution and therefore whether the role of domain-general systems is restricted to sentences that require reinterpretation.

Our data indicate that the *cognitive* system involved in high-level aspects of sentence comprehension involves domain-general processes that are recruited for other non-sentential tasks, in particular those involving response selection. Such cognitive overlap must have its basis in common *neural* systems involved in both sentence comprehension and in non-sentential tasks. Accordingly, we suggest that this overlapping neural circuitry can likely be localised to the LIFG, which may be part of a cognitive control circuit crucial to both sentential and non-sentential processing (January et al., 2008; Novick et al., 2005). This view is also consistent with the fact that fMRI studies of response selection (Binder, Liebenthal, Possing, Medler, & Ward, 2004; Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002) and semantic ambiguity resolution (Mason & Just, 2007; Rodd, Longe et al., 2010; Rodd et al., 2005; Zempleni et al., 2007) reveal activation in very similar, if not identical, regions of LIFG. Furthermore, a number of fMRI studies have shown neural correlates of dual-task interference effects in LIFG (Dux, Ivanoff, Asplund, & Marois, 2006; Jiang, 2004). Thus, a range of behavioural and neuroimaging data converge in suggesting that the dual-task interference observed in the present study may reflect a common contribution of inferior frontal processes to linguistic and non-linguistic selection processes. We predict that tests of dual-task interference due to syntactic complexity of sentences would similarly implicate domain-general cognitive processes. Such conclusions challenge proposals that localise specialised linguistic functions in left inferior frontal regions (see, for instance, Grodzinsky & Santi, 2008).

In summary, these experiments provide converging behavioural evidence that the neural/cognitive system(s) that are engaged in high-level aspects of sentence comprehension are also involved in simple non-sentential decision tasks such as case-judgement. This supports the wider view that higher-level aspects of sentence comprehension, such as semantic selection and reinterpretation, rely on cognitive and neural systems that are not specialised for sentence comprehension, but are also recruited for a number of non-sentential tasks in which participants are required to select an appropriate response from a set of alternatives. Dual-task studies such as these can provide a rich source of evidence about the extent to which aspects of sentence comprehension recruit cognitive/neural systems that are also recruited for other tasks. By observing the conditions under which dual-task interference effects emerge, for a range of different linguistic manipulations and secondary tasks, we can obtain a better understanding of the extent to which sentence comprehension is reliant on domain-general processes. For instance, further support for the view that domain-general selection processes are involved in sentence comprehension would be provided by demonstrations that *no* interference is seen for a task at a similar difficulty level to the case-judgement task, but that does *not* involve selection. We have conducted an experiment using the method and materials from

Experiment 1 (Rodd, Johnsrude, Ford, & Davis, 2010) in which the case-judgement task is replaced by a task in which participants are required to detect a small dot, which occurs on 50% of the trials. As predicted by the view that interference effects should arise from response-selection processes, this simple-RT task did not show a latency difference for dots presented during sentences with or without ambiguous words. However, although this observation is consistent with the idea that tasks not involving selection do not interfere with ambiguity resolution, response latencies were overall faster on this task (approximately 410 ms, compared to 540 ms in Experiment 1) and so it is probably not matched to the case-judgement task on difficulty. While it would be possible to increase these latencies by, for example, degrading the visual stimuli, this would likely introduce a response selection component, as participants would be selecting an appropriate response in the context of a visually ambiguous stimulus. The creation of an appropriate 'control' task, matched to case-judgement as far as possible but without a response selection component, is not straightforward.

Previous behavioural and fMRI studies have suggested that the process of selecting task-relevant material may, to some extent, be dissociable for other related executive functions such as response inhibition (e.g., Nee & Jonides, 2009) and selective attention (e.g., Persson, Welsh, Jonides, & Reuter-Lorenz, 2007). We suggest that future studies using this dual-task paradigm could help to reveal the extent to which these different executive functions may (or may not) rely on common cognitive processes.

Finally, it is worth remembering that conversation is in itself a dual-task situation. Conversational partners must simultaneously comprehend an ongoing utterance whilst preparing their own response. Our experimental findings are therefore a worthwhile reminder of the difficulties created by the presence of ambiguity in spoken language and the skill with which listeners resolve these ambiguities in the face of other, competing, cognitive demands.

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References

Binder, J. R., Liebenthal, E., Possing, E. T., Medler, D. A., & Ward, B. D. (2004). Neural correlates of sensory and decision processes in auditory object identification. *Nature Neuroscience, 7*, 295–301.

Bunge, S. A., Hazeltine, E., Scanlon, M. D., Rosen, A. C., & Gabrieli, J. D. (2002). Dissociable contributions of prefrontal and parietal cortices to response selection. *Neuroimage, 17*, 1562–1571.

Caramazza, A., & Zurif, E. B. (1976). Dissociation of algorithmic and heuristic processes in sentence comprehension: Evidence from aphasia. *Brain and Language, 3*, 572–582.

Dapretto, M., & Bookheimer, S. Y. (1999). Form and content: Dissociating syntax and semantics in sentence comprehension. *Neuron, 24*, 427–432.

Dronkers, N. F., Wilkins, D. P., Van Valin, R. D., Redfern, B. B., & Jaeger, J. J. (2004). Lesion analysis of the brain areas involved in language comprehension. *Cognition, 92*, 145–177.

Duncan, J., & Owen, A. M. (2000). Common regions of the human frontal lobe recruited by diverse cognitive demands. *Trends in Neurosciences, 23*, 475–483.

Dux, P. E., Ivanoff, J., Asplund, C. L., & Marois, R. (2006). Isolation of a central bottleneck of information processing with time-resolved FMRI. *Neuron, 52*, 1109–1120.

Fodor, J. A. (1983). *The modularity of the mind*. Cambridge, MA: MIT Press.

Forster, K. I., & Forster, J. C. (2003). A Windows display program with millisecond accuracy. *Behavior Research Methods Instruments & Computers, 35*, 116–124.

Grodzinsky, Y. (2000). The neurology of syntax: Language use without Broca's area. *Behavioral and Brain Sciences, 23*, 1–21.

Grodzinsky, Y., & Amunts, K. (2006). *Broca's region*. Oxford: Oxford University Press.

Grodzinsky, Y., & Santi, A. (2008). The battle for Broca's region. *Trends in Cognitive Sciences, 12*, 474–480.

Hagoort, P. (2005). On Broca, brain, and binding: A new framework. *Trends in Cognitive Sciences, 9*, 416–423.

January, D., Trueswell, J. C., & Thompson-Schill, S. L. (2009). Co-localization of stroop and syntactic ambiguity resolution in Broca's area: Implications for the neural basis of sentence processing. *Journal of Cognitive Neuroscience, 21*, 2434–2444.

Jiang, Y. (2004). Resolving dual-task interference: An fMRI study. *Neuroimage, 22*, 748–754.

Kaan, E., & Swaab, T. Y. (2002). The brain circuitry of syntactic comprehension. *Trends in Cognitive Sciences, 6*, 350–356.

Lucas, M. (1999). Context effects in lexical access: A meta-analysis. *Memory and Cognition, 27*, 385–598.

Mason, R. A., & Just, M. A. (2007). Lexical ambiguity in sentence comprehension. *Brain Research, 1146*, 115–127.

Moss, H. E., Abdallah, S., Fletcher, P., Bright, P., Pilgrim, L., Acres, K., et al. (2005). Selecting among competing alternatives: Selection and retrieval in the left inferior frontal gyrus. *Cerebral Cortex, 15*, 1723–1735.

Nee, D. E., & Jonides, J. (2009). Common and distinct neural correlates of perceptual and memorial selection. *NeuroImage, 45*, 963–975.

Novick, J. M., Trueswell, J. C., & Thompson-Schill, S. L. (2005). Cognitive control and parsing: Reexamining the role of Broca's area in sentence comprehension. *Cognitive Affective & Behavioral Neuroscience, 5*, 263–281.

Pashler, H. (1994). Dual-task interference in simple tasks: Data and theory. *Psychological Bulletin, 116*, 220–244.

Persson, J., Welsh, K. M., Jonides, J., & Reuter-Lorenz, P. A. (2007). Cognitive fatigue of executive processes: Interaction between interference resolution tasks. *Neuropsychologia, 45*, 1571–1579.

Pollatsek, A., & Well, A. D. (1995). On the use of counterbalanced designs in cognitive research: A suggestion for a better and more powerful analysis. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21*, 785–794.

Rodd, J. M., Davis, M. H., & Johnsrude, I. S. (2005). The neural mechanisms of speech comprehension: fMRI studies of semantic ambiguity. *Cerebral Cortex, 15*, 1261–1269.

Rodd, J. M., Johnsrude, I. S., Ford, M., & Davis, M. H. (2010). Understanding speech in dual-task conditions: The impact of semantic ambiguity. Poster session presented at Psycholinguistic Approaches to Speech Recognition in Adverse Conditions. EPS Workshop, University of Bristol, 8–10 March, 2010. <http://language.psy.bris.ac.uk/workshop/pdfs/Bristol-2010_P218.pdf>.

Rodd, J. M., Longe, O. A., Randall, B., & Tyler, L. K. (2010). The functional organisation of the fronto-temporal language system: Evidence from syntactic and semantic ambiguity. *Neuropsychologia, 48*, 1324–1335.

Simon, J. R. (1969). Reactions toward the source of stimulation. *Journal of Experimental Psychology, 81*, 174–176.

Swaab, T. Y., Brown, C., & Hagoort, P. (1998). Understanding ambiguous words in sentence contexts: Electrophysiological evidence for delayed contextual selection in Broca's aphasia. *Neuropsychologia, 36*, 737–762.

Swinney, D. A. (1979). Lexical access during sentence comprehension: (Re)consideration of context effects. *Journal of Verbal Learning and Verbal Behavior, 18*, 645–659.

Thompson-Schill, S. L., D'Esposito, M., Aguirre, G. K., & Farah, M. J. (1997). Role of left inferior prefrontal cortex in retrieval of semantic knowledge: A reevaluation. *Proceedings of the National Academy of Sciences of the United States of America, 94*, 14792–14797.

Tombu, M., & Jolicoeur, P. (2003). A central capacity sharing model of dual-task performance. *Journal of Experimental Psychology: Human Perception and Performance, 29*, 3–18.

Twilley, L. C., & Dixon, P. (2000). Meaning resolution processes for words: A parallel independent model. *Psychonomic Bulletin & Review, 7*, 49–82.

Willems, R. M., & Hagoort, P. (2009). Broca's region: Battles are not won by ignoring half of the facts. *Trends in Cognitive Sciences, 13*, 101.

Zempleni, M. Z., Renken, R., Hoeks, J. C., Hoogduin, J. M., & Stowe, L. A. (2007). Semantic ambiguity processing in sentence context: Evidence from event-related fMRI. *NeuroImage, 34*, 1270–1279.