

Neurocognitive mechanisms for processing inflectional and derivational complexity in English

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In the current paper we discuss the mechanisms that underlie the processing of inflectional and derivational complexity in English. We address this issue from a neurocognitive perspective and present evidence from a new fMRI study that the two types of morphological complexity engage the language processing network in different ways. The processing of inflectional complexity selectively activates a left-lateralised fronto-temporal system, specialised for combinatorial grammatical computations, while derivational complexity primarily engages a distributed bilateral system, argued to support whole-word, stem based lexical access. We discuss the implications of our findings for theories of the processing and representation of morphologically complex words.

Key words: morphology, brain, inflection, derivation

INTRODUCTION

Morphemes are the smallest meaningful units in language (Henderson, 1985), flexibly combined to create larger grammatical and lexical structures and to allow the language user to communicate an infinite number of ideas. For instance, English stem morphemes like *jump* and *dark* are combined with suffix morphemes like *-ed*, *-s*, *-ness*, or *-ly* to create words like *jumped*, *jumps*, *darkness* and *darkly*, as well as many other different words with different grammatical and lexical properties. Language comprehension requires the listener to recognise these complex words, and associate them with their corresponding cognitive representations. It is as yet unresolved to what extent these processes and representations are driven by the underlying morphological structure of this class of words. We address the issue of processing and representation of morphologically complex words in English from a neurocognitive perspective and present existing, as well as new evidence, to illustrate our claims.

Psycholinguistic data show that morphological structure of complex words affects their processing: the recognition of a morphologically complex word like *darkness* is influenced both by its frequency as a whole word and the frequency of its constituent morphemes (Baayen, Dijkstra, & Schreuder, 1997; Burani & Caramazza, 1987; Cole, Beauvillain, & Segui, 1989; Taft, 1979), as well as by prior presentation of another morphologically related word (e.g., Longtin & Meunier, 2005; Rastle, Davis, Marslen-Wilson, & Tyler, 2000; Marslen-Wilson, Tyler, Waksler, & Older, 1994; Marslen-Wilson, Božić, & Randall, 2008). Findings like this were taken to suggest that the processing of morphologically complex words involves stem-suffix decomposition at some processing stage, and is also reflected in the structure of their mental representations (e.g., Taft, 2004). Other authors emphasise a major role for factors like semantic compositionality, affix productivity or frequency of the constituent morphemes in determining whether a complex word is stored and processed as a whole or with respect to its morphological structure (Bertram, Schreuder, & Baayen, 2000; Marslen-Wilson et al., 1994). Another view holds that morphologically complex words are stored as whole forms (e.g., Butterworth, 1983), but with preserved underlying morphological structure in the representations of more compositional complex words (Clahsen, Sonnenstuhl, & Blevins, 2003; Marslen-Wilson, 2007). These contrasting views are still actively debated in the psycholinguistic literature.

To dissociate between these different perspectives, it is first necessary to draw a distinction between different types of morphologically complex words. In a language like English, morphologically complex words are formed by combining stems with inflectional or derivational morphemes (as well as by compounding two stems, which is not considered here due to the distinct properties of compounds). It has been argued that the functional roles of inflectional and derivational morphemes differ substantially: inflectional morphemes (*-ed*, *-s*, *-ing*) serve a purely grammatical function, adjusting the stem to the syntactic requirements of a sentence (i.e., marking it as a past tense e.g., *play+ed*; marking agreement between words in a sentence e.g., *he plays*; or expressing the grammatical role of a noun as subject or object in case-marking languages). Inflectional suffixes do not add new semantic information to the stem: *played* or *plays* differ only in tense/person/number from the stem *play*. Another major characteristic of inflectional processes is that they are regular and predictable: the morpheme *-ed* applies across the board to form the English regular past tense. Inflected words are therefore considered to be linguistic variants of the original form, fully compositional with respect to the meaning of the stem combined with the grammatical properties of the inflectional suffix (Bickel & Nichols, 2006; Marslen-Wilson, 2007). In contrast to this, adding derivational morphemes like *-er*, *-ness*, *-ly*, or *-ish* to a stem creates new lexical entries in the mental lexicon, with different meanings and usually a different grammatical category (e.g., *play* vs. *player*). The stem-suffix connection in derived words is lexicalised and, compared to inflected forms, the meaning of derived words is less predictable from the combination of the meaning of

their constituent morphemes. It should be noted, however, that the criteria for separating inflectional from derivational processes are not universally agreed, and some authors have called into question the validity of the distinction between the two sets (e.g., Bauer, 2004; Booij, 2005; Lieber, 1980).

These persistent controversies about the role of morphological structure in processing complex words, and about the distinction between inflection and derivation, underline the need to probe the neural systems that support the processing and representation of these forms. Similarities and differences in the neural correlates of processes involving inflected and derived words would provide important new constraints on the proposed views. Our recent work has aimed to shed light on these issues by investigating the neurocognitive signatures of the processing and representation of inflected and derived forms in English. We tested what processing mechanisms they engage, and how far they are comparable across these two morphological domains.

We approached these issues from a dual system perspective on the neurobiological systems that support language comprehension. Ample neuroimaging and neuropsychological evidence shows that language comprehension engages a distributed network of bilateral frontal and temporal brain areas (e.g., Binder, Frost, Hammeke, Cox, Rao, & Prieto, 1997; Božić, Tyler, Ives, Randall, & Marslen-Wilson, 2010; Davis & Johnsrude, 2003, Tyler, Stamatakis, Post, Randall, & Marslen-Wilson, 2005). Further evidence suggests that this language processing network consists of two functionally different systems: one distributed over both hemispheres, which supports general processing demands associated with whole-word lexical access, and the other in the left hemisphere, supporting combinatorial grammatical computations (Božić et al., 2010; Marslen-Wilson & Tyler, 2007).

In an earlier experiment (Božić et al., 2010) we tested how inflectionally complex words in English engage this distributed fronto-temporal network and its two systems. Inflectional complexity was realised through the presence of the inflectional rhyme pattern (IRP) – a phonological pattern in English which signals that the ending of a complex word may be an inflectional affix and not part of the stem. It is defined in terms of the phonological properties of the two most frequent regular inflections in English {-ed} and {-s}. These are both realised by a coronal consonant (*d, t, s, z*) at word offset that agrees in voice with the preceding segment (e.g., *played, dogs*). The results showed that words ending in an IRP (whether they were real inflections, e.g., *played*, or words with an IRP ending where this was not a real inflection, e.g., *trade, trend*) selectively activated the left-lateralised fronto-temporal system, primarily in the dorsal areas of the inferior frontal gyrus (BA45). This contrasted with the activation for words that make perceptual, non-linguistic demands on the language processing system (e.g., words like *claim* that have another word (*clay*) embedded in them, which triggers increased competition between the whole word and the embedded stem). This type of word activated the bilateral system. We argued that the neurocognitive properties of inflected words converge with

their linguistic properties (Bickel & Nichols, 2007; Marslen-Wilson, 2007) to suggest that inflections undergo an obligatory decomposition in the recognition process; and are processed and represented with respect to their morphological structure. The left-lateralised combinatorial system supports this decomposition, by separating inflected forms into stems, which carry lexical meaning, and inflectional suffixes, which convey grammatical information but do not interact with the meaning of the stem.

In a follow-up experiment we investigated the neuro-cognitive distribution of the mechanisms for processing and representation of derivationally complex words (Božić & Marslen-Wilson, 2010; Božić et al., 2013), asking whether they interface with the fronto-temporal language network in the same way as inflectional morphology, engaging the same left-lateralised combinatorial and decompositional system. To test this we manipulated the semantic compositionality and suffix productivity of derived words, creating sets of items that are more or less likely to trigger left-lateralised decompositional processes. We hypothesised that highly compositional semantically transparent words with productive suffixes, like *bravely*, would be most likely to engage these processes – in the same way as they are engaged by inflected forms – while semantically opaque words with unproductive suffixes, such as *breadth*, would be least likely to engage them.

The results showed no evidence for selective activation of the left-lateralised system, even for the most compositional derived words like *bravely*. Instead, we saw activation in the distributed bilateral system, supporting the processing demands associated with accessing whole word lexical representations. This bilateral activation primarily reflected the difficulty of separating the word from its competing alternatives – in the case of derived words this would typically be the word stem or pseudostem (e.g., *warm* in *warmth* or *arch* in *archer*). The semantic and linguistic transparency of derived words still affected this process, such that stronger bilateral activation emerged for words like *breadth* than words like *bravely*. We argue that this overall pattern results from the linguistic properties of morphologically complex derived words, whose meaning is often not compositional with respect to the meaning of their constituent morphemes (e.g. *drawer*, *archer*, *witness*, *infantry*) and is available only when a derived word is considered as a whole form. This is why lexical access for derived words does not require morpho-phonological parsing and segmentation in the left hemisphere, suggesting that they are represented as lexicalised full-form entries, and not assembled or disassembled online in the same manner as inflections.

These full-form representations may nevertheless still preserve their underlying morphological structure, particularly for transparent words with productive suffixes like *bravely* (c.f., Clahsen et al., 2003; Marslen-Wilson, 2007). For these words, the preserved morphological structure and the conceptual closeness to the competing stem (*brave*) would reduce the processing load associated with lexical access, resulting in weaker activation of the bihemispheric system – but they would still not trigger a selective activation of the left-lateralised decompositional system. This interpretation is also consistent with psycholinguistic data (though primarily in the visual domain) showing that

the underlying morphemic structure of derived words can be detected when it is directly and explicitly primed (e.g., Longtin & Meunier, 2005; Rastle et al., 2000; Marslen-Wilson et al., 2008).

Here we present further evidence that inflected and derived forms in English differentially engage the language processing network. The current fMRI experiment aimed to test the neurocognitive distribution of inflectional and derivational processing by investigating the hemispheric lateralisation of the processes triggered by the two word types. Sets of inflected and derived forms were constructed to provide a comparable range of possible triggers for combinatorial processing, where the inflected set is expected to engage the LH system. This set, following Božić et al. (2010), consisted of words that were either real regular inflected forms (e.g., *played*), fully decomposable into a real stem and suffix; words containing a pseudostem and an IRP ending (e.g., *trade*, which can be analysed as *tray+ed*); or words with an IRP ending but no onset embedded stem (e.g., *trend*, where *tren* is not a real English word).

For the derived condition we constructed a parallel set, consisting of words that are semantically compositional with respect to the meaning of their constituent morphemes (e.g. *bravely*), words that have a potential stem and a potential derivational suffix, but whose meaning could not be obtained from the meaning of the constituents (e.g., *corner*, analysable as *corn+er*), and words containing a derivational suffix but no onset embedded stem (e.g., *blemish*). Based on our earlier results, we expected selective activation of the decompositional left-hemisphere system for the processing of morphologically complex inflected words, leading to stronger left-lateralisation for inflected words than for derived words.

Inflected and derived words were intermixed and presented alongside filler items and a well matched acoustic baseline, used to isolate lexical processing from lower-level auditory processing. This baseline, called musical rain (MR), shares the complex auditory properties of a speech signal but cannot be interpreted as speech (see Uppenkamp, Johnsrude, Norris, Marslen-Wilson, & Patterson, 2006 and Božić et al. 2010 for details).

Methods

Participants. Thirteen right-handed native speakers of British English participated in the study. All were screened for neurological or developmental disorders and gave informed consent. The study was approved by the Peterborough and Fenland Ethical Committee (UK).

Stimuli. Both inflected and derived conditions consisted of three sets of 40 words each, constructed to provide a parallel range of possible triggers for morphological processing across the two sets (Table 1)¹. As described above, the inflectional set contained 40 words that were real regular English inflections (e.g., *played*), 40 pseudoregulars (e.g., *trade*), and 40 words with an IRP ending but no stem (e.g., *trend*). The derivational set consisted of three parallel groups: 40 semantically transparent forms (e.g. *bravely*), 40 words with a pseudostem and a derivational affix (e.g., *corner*), and 40 words ending in a potential derivational suffix but with

¹ The experiment contained a further four unaffixed conditions, designed to address a different set of questions. They are treated as fillers here, and the relevant comparisons will be reported elsewhere.

no stem (e.g., *blemish*). A full list of test stimuli is given in the Appendix. All words within inflectional and derivational sets and their embedded stems were matched on word and lemma frequency, syllable number, and sound file length (all $p > .1$). The test words were mixed with fillers and 200 acoustic baseline trials.

Table 1. Stimuli properties

Inflected	Derived	suffix	stem
played (N=40)	bravely (N=40)	Y	real
trade (N=40)	corner (N=40)	Y	pseudo
trend (N=40)	blemish (N=40)	Y	N

Procedure. Following Božić et al. (2010; 2013), the participants performed a gap detection task. This is a non-linguistic task that engages lexical processing but at the same time keeps the task requirements constant across words and the acoustic baseline trials (Mattys & Clark, 2002; Mattys, Pleydell-Pearce, Melhorn, & Whitecross, 2005). Short silent gaps (400 ms) were inserted in approximately 10% of trials (40 filler words and 40 musical rain trials) and participants were asked to decide as quickly and accurately as possible whether a word or a musical rain sound contains a silence gap or not. For sounds which did not contain a silence gap participants pressed the button under their index finger, and for sounds that contained a gap participants pressed the button under their middle finger. Only gap-absent trials were subsequently analysed.

The words were recorded in a sound-proof room by a female native speaker of British English onto a DAT recorder. They were then digitized at a sampling rate of 22kHz with 16 bit conversion and stored as separate files using CoolEdit. CoolEdit was also used for gap insertion. Items were presented using in-house software and participants heard the stimuli binaurally over NNL headphones. A total of 720 trials were presented in 4 blocks of 180 items each, pseudorandomised with respect to their type (test, filler, baseline) and presence or absence of gaps. There were 5 items at the beginning of each block to allow the signal to reach equilibrium. The experiment started with a short practice session outside the scanner, where participants were given feedback on their performance. Participants were instructed to keep their eyes closed during the scanning.

Scanning was performed on a 3T Trio Siemens Scanner at the MRC-CBU, Cambridge, using a fast sparse imaging protocol to minimize the interference of scanner noise with auditory processing (gradient-echo EPI sequence, TR = 3.4 s, TA = 2 s, TE = 30ms, flip angle 78 degrees, matrix size 64 x 64, FOV = 192 x 192 mm, 32 oblique slices 3mm thick, 0.75mm gap). MPRAGE T1-weighted scans were acquired for anatomical localization. Data were analysed using SPM5 software (<http://www.fil.ion.ucl.ac.uk/spm/>). Pre-processing was performed using the automatic analysis library (<http://www.cambridgeuroimaging.com/aawiki/>), and involved image realignment to correct for movement, segmentation and spatial normalisation of functional images to the MNI reference brain, and smoothing with an 10 mm isotropic Gaussian kernel. The data for each subject were then analysed using the general linear model (GLM). Motion regressors were included as covariates of no interest to account for any residual movement artefacts. A high-pass filter with a 128s cut-off was applied to remove low-frequency noise. The BOLD response for each event was modelled with the canonical HRF and its temporal derivative. Contrast images were combined into a group random effects analysis, and results thresholded at uncorrected voxel level of $p < .001$ and cluster level of $p < .05$ corrected for multiple comparisons. To run laterality analyses, EPI images were normalised onto a symmetrical T1 template and the standard first level analysis was performed. The resulting SPM maps were flipped along the Y axis and compared with the original maps in a series of t-tests (Liegeois, Connelly, Salmond, Gadian, Vargha-Khadem & Baldeweg, 2002). This procedure tests for activation that is stronger in the left than in the right hemisphere, and vice versa.

Results

Given previous results and our specific question, the analysis focused on a volume of interest (VOI) encompassing bilateral fronto-temporal regions. The VOI was constructed using WFU Pickatlas to include bilateral temporal lobes (superior, middle and inferior temporal gyri, angular gyrus), inferior frontal gyri (pars orbitalis, pars opercularis, pars triangularis, precentral gyrus), insula and the anterior cingulate.

We first established the network that supports lexical processing. Subtracting the activation elicited by the musical rain baseline from the activation for words showed the expected pattern of distributed bilateral activity, consistent with previous findings (Binder et al., 1997; Božić et al., 2010; Davis & Johnsruide, 2003, Tyler et al., 2005). Specifically, lexical processing activated bilateral middle temporal gyri (BA 21, peaks at $-66 -26 -8$ and $62 -8 -12$) and the surrounding superior and inferior temporal regions, bilateral angular gyri (BA 39, peaks at $-48 -68 28$ and $54 -64 28$), anterior cingulate (peak at $4 50 12$) and the left inferior frontal region (BA47, $-38 30 -16$). The laterality analyses confirmed that this activation pattern is stronger in the left than in the right hemisphere, with stronger L than R activation in inferior frontal and superior and inferior temporal areas (Figure 1 and Table 2).

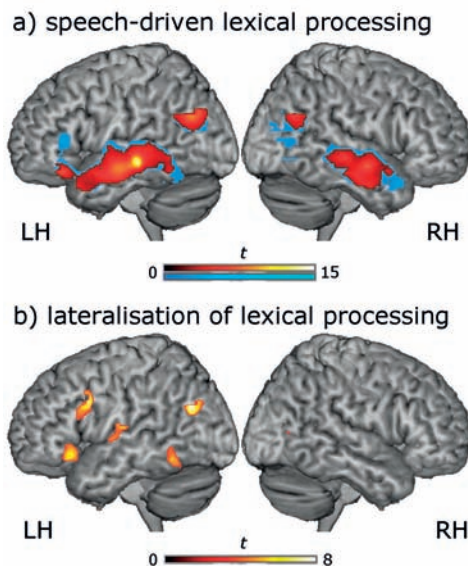


Figure 1. a) Significant activation for speech-driven lexical processing (words – MR baseline), rendered onto the surface of a canonical brain. Red shows activation thresholded at $p < 0.001$ voxel and $p < 0.05$ cluster level corrected for multiple comparisons; blue shows activation at the lower threshold of $p < 0.01$ voxel and $p < 0.05$ cluster level corrected for multiple comparisons; b) Significant lateralisation of speech-driven lexical processing rendered onto the surface of a canonical brain. Activation is thresholded at $p < 0.001$ voxel and $p < 0.05$ cluster level corrected for multiple comparisons.

Table 2. a) Activation for speech-driven lexical processing (words – MR baseline); b) Lateralisation of speech-driven lexical processing. All results are significant at $p < 0.001$ voxel and $p < 0.05$ cluster level corrected for multiple comparisons.

Regions	Cluster	Voxel	Coordinates		
A: Speech-driven lexical processing	Extent	Z	x	y	z
L middle temporal gyrus	2226	6.35	-66	-26	-8
L inferior temporal gyrus		5.36	-30	-36	-18
L inferior temporal gyrus		5.25	-42	-42	-18
L angular gyrus	544	5.27	-46	-68	28
R middle temporal gyrus	860	5.00	62	-8	-12
R middle temporal gyrus		4.63	70	-28	-4
R inferior temporal gyrus		4.38	60	-8	-26
L inferior frontal gyrus (BA47)	129	4.98	-38	30	-16
L inferior frontal gyrus (BA47)		3.51	-36	36	-10
R angular gyrus	230	4.67	54	-64	28
Anterior cingulate	907	4.61	4	50	12
Anterior cingulate		4.53	-8	36	-10
Anterior cingulate		4.49	8	30	-10
R fusiform gyrus	229	4.53	34	-38	-16
R parahippocampal area		4.12	32	-26	-14
R parahippocampal area		3.42	32	-36	-8
B: Lateralisation of lexical processing					
L angular gyrus	170	4.80	-44	-68	28
L inferior frontal gyrus (BA44)	266	4.65	-52	12	30
L inferior frontal gyrus (BA44)		3.89	-48	12	38
L inferior frontal gyrus (BA45)		3.52	-38	26	12
L inferior frontal gyrus (BA47)	267	4.63	-38	28	-10
R medial middle temporal gyrus	388	4.61	38	-34	6
R medial middle temporal gyrus		4.13	36	-42	12
R medial middle temporal gyrus		3.86	38	-52	6
L inferior temporal gyrus	376	4.53	-46	-50	-10
L middle temporal gyrus		3.32	-54	-38	-10
L superior temporal gyrus	80	4.15	-64	-16	12
L superior temporal gyrus		3.66	-58	-6	2

To test for the laterality of the mechanisms that underlie the processing of morphologically complex inflected and derived words, the laterality analysis was run separately on the lexical processing triggered by the inflected and the derived set. The results revealed more left-lateralised activation for the inflected than for the derived set (Figure 2 and Table 3). For the inflected words, significant left-lateralised activation was seen in dorsal and ventral parts of the inferior frontal gyrus (LIFG BA 44/45 and BA 47, respectively), inferior temporal and angular gyri. For the derived set, significant activation only emerged in the ventral parts of the left hemisphere, specifically in the BA 47 area of left inferior frontal gyrus and superior and inferior temporal areas (BA 22 and BA 37 respectively).

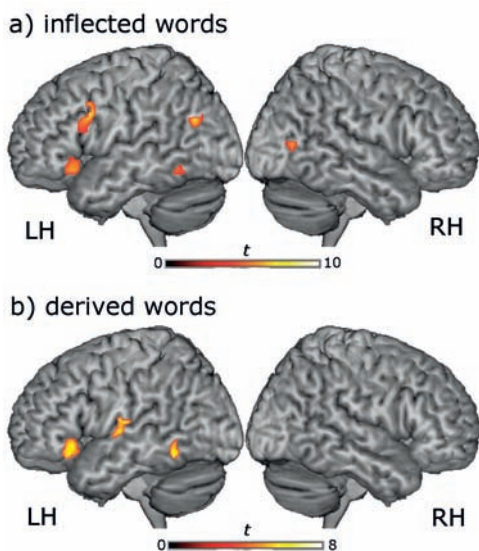


Figure 2. Significant lateralisation of the lexical activation for a) the inflected set; b) the derived set, rendered onto the surface of a canonical brain. Activation is thresholded at $p < 0.001$ voxel and $p < 0.05$ cluster level corrected for multiple comparisons.

Table 3. Significant lateralisation for a) inflected words and b) derived words. All results are significant at $p < 0.001$ voxel and $p < 0.05$ cluster level corrected for multiple comparisons.

Regions	Cluster	Voxel	Coordinates		
A: Inflected words	Extent	Z	x	y	z
L inferior temporal gyrus	182	5.05	-46	-52	-10
L inferior temporal gyrus		3.87	-44	-58	-18
R superior temporal gyrus	83	4.60	42	-30	4
R middle temporal gyrus	179	4.52	34	-40	18
R middle temporal gyrus		4.19	40	-64	10
R middle temporal gyrus		3.96	46	-70	8
L inferior frontal gyrus (BA44/45)	226	4.40	-50	14	28
L inferior frontal gyrus (BA45)		3.48	-44	26	20
L angular gyrus	87	4.25	-44	-68	28
L inferior frontal gyrus (BA47)	198	4.10	-40	24	-10
B: Derived words					
L inferior temporal gyrus	282	4.61	-50	-50	-12
L inferior temporal gyrus		3.78	-40	-46	-22
L inferior frontal gyrus (BA47)	254	4.40	-38	28	-10
L inferior frontal gyrus (BA47)		3.81	-50	26	-8
R medial temporal gyrus	100	4.26	38	-34	8
L superior temporal gyrus	107	4.04	-64	-16	12
L superior temporal gyrus		3.84	-58	-10	4

To provide a more detailed view of the results, we also assessed processing laterality for each of the six conditions individually (see Table 4). Consistent with the results from the joint inflected set, each of the three inflectional conditions (*played*, *trade* and *trend*) triggered significant left-lateralised activation in both dorsal and ventral parts of the inferior frontal gyrus (BA 44/45 and BA 47 respectively). The laterality results for the three derived conditions separately (*bravely*, *archer* and *blemish*) also revealed a pattern consistent with the joint results – they all showed significant left-lateralised activation only in the ventral part of the inferior frontal gyrus (BA 47). However, we also saw a marginally significant left lateralisation effect ($p < 0.1$ cluster-level corrected) in the dorsal part of the LIFG (BA 44) for the *bravely* condition. Finally, we tested for possible differences between conditions in the inflected and the derived set separately. No reliable differences emerged for either set.

Table 4. Significant lateralisation for each of the six conditions separately. For brevity, only the most significant peak for each cluster is reported. Results are significant at $p < 0.001$ voxel and $p < 0.05$ cluster level corrected for multiple comparisons.

Regions	Cluster Extent	Voxel Z	Coordinates		
			x	y	z
1. Played					
L inferior frontal gyrus (BA 44)	85	3.92	-50	16	26
L inferior frontal gyrus (BA 47)	76	3.74	-40	28	-10
2. Trade					
L inferior frontal gyrus (BA 44/45)	337	4.84	-48	16	28
L inferior temporal gyrus	206	4.45	-48	-50	-8
L inferior frontal gyrus (BA 47)	238	4.37	-40	24	-12
R medial temporal gyrus	142	4.33	40	-34	4
3. Trend					
L inferior frontal gyrus (BA 44/45)	168	4.43	-52	12	30
L inferior frontal gyrus (BA 47)	140	3.96	-42	22	-8
L inferior temporal gyrus	104	3.75	-48	-54	-12
4. Bravely					
L inferior frontal gyrus (BA 47)	98	3.72	-40	28	-6
L inferior frontal gyrus (BA 44)**	64	3.92	-52	12	30
5. Archer					
L inferior frontal gyrus (BA 47)	281	4.79	-38	26	-8
R medial temporal gyrus	127	3.79	40	-34	12
L superior temporal gyrus	74	4.95	-64	-16	12
6. Blemish					
L inferior temporal gyrus	286	5.23	-52	-52	-14
L inferior temporal gyrus	100	4.16	-66	-16	12
L inferior frontal gyrus (BA 47)	141	3.78	-38	28	-12

** marginally significant at $p < 0.1$ cluster level corrected for multiple comparisons

DISCUSSION

The current paper focuses on the neuro-cognitive mechanisms for processing inflectional and derivational complexity in English. It presents new evidence that the two types of morphological complexity differentially engage the fronto-temporal language network, which has significant implications for the discussion about the way they are processed and represented in the mental lexicon.

The general neuroimaging literature shows that language processing activates a distributed network of bilateral fronto-temporal regions, with the left hemisphere engaged more strongly than the right (Binder et al., 1997; Božić et al., 2010; Davis & Johnsruide, 2003, Tyler et al., 2005). Consistent with this, we find speech-driven lexical processing in bilateral middle and superior temporal gyri, angular gyri, anterior cingulate and the left inferior frontal gyrus, with stronger activation on the left than on the right in temporal and frontal brain areas.

More importantly, we also see that this language processing network responds differently to inflectionally and derivationally complex words. Our previous results (Božić et al., 2010) showed that regular inflectional morphology selectively engages an assumed combinatorial processing system in the left hemisphere. A regularly inflected word like *played* is a predictable and compositional combination of a stem *play* and a grammatical morpheme *-ed*, whose processing requires access to the lexical representation of the stem (which carries the lexical meaning) and extraction of the morpheme *-ed* (which conveys grammatical information but does not interact with the meaning of the stem). These decompositional processes trigger increased activation in left inferior frontal areas, as well as left fronto-temporal interactions. This is consistent with earlier neuroimaging and neuropsychological evidence for the key role of left fronto-temporal regions in the processing of grammatically complex sequences that require parsing and segmentation during language comprehension (e.g., Friederici, Fiebach, Schlesewsky, Bornkessel, & von Cramon, 2006; Goodglass, Christiansen, & Gallagher, 1993; Marslen-Wilson & Tyler, 2007; Shtyrov, Pihko, & Pulvermuller, 2005; Tyler et al., 2005).

The results of the current laterality experiment suggest more specific hypotheses about the neural architecture that underlies these decompositional processes. These can be stated in terms of the emerging anatomical and functional separation between dorsal and ventral language processing streams (Friederici, 2009; Hickok & Poeppel, 2007; Marslen-Wilson & Tyler, 2007; Rolheiser, Stamatakis, & Tyler, 2011; Scott & Johnsruide, 2003). The dorsal stream, claimed to be more prominent in the left than the right hemisphere, runs along the arcuate/superior longitudinal fasciculus (AF/SLF) to connect posterior temporal and inferior parietal regions with dorsal parts of the inferior frontal gyrus (Catani, Jones, & Ffytche, 2005; Griffiths, Marslen-Wilson, Stamatakis, & Tyler, 2013; Hickok & Poeppel, 2007; Saur, Kreher, Schnell, Kummerer, Kellmeyer, Vry, Umarova, Musso, Glauche, Abel, Huber, Rijntjes, Hennig, & Weiller, 2008). A more bilaterally distributed ventral processing stream, primarily involving the extreme capsule complex, connects middle and inferior temporal cortices with ventral parts of the inferior frontal gurus.

Functionally, the ventral stream has been associated with semantic processes and sound-to-meaning mapping (Friederici, 2009; Saur et al., 2008), while the dorsal stream plays an important role in grammatical and morphological processing (Rolheiser et al., 2011; Wright, Stamatakis, & Tyler, 2012). Since the processing of inflected words involves both parsing of a grammatical morpheme and access to the lexical meaning of the stem, it would require the engagement of both processing streams (Griffiths et al., 2013; Rolheiser et al., 2011), with the dorsal stream underlying morpho-phonological decompositional functions.

This provides a framework for explaining the different patterns of lateralisation seen in this experiment. Inflected words triggered significant left-lateralised activation in several areas of the language processing network: dorsally, in the pars opercularis and pars triangularis areas of inferior frontal gyrus (BA 44/45) and angular gyrus (BA 39); and ventrally in pars orbitalis (BA 47) and inferior temporal gyrus. This pattern of joint dorsal and ventral LIFG activation also held for each of the three inflectional conditions separately. The ventral effects in BA 47 are common to both the derivational and the inflectional sets, and arguably reflect general processing demands associated with accessing word meaning, and degrees of difficulty in separating between competing alternatives – for example, the strongest effects in BA47 are for the *trade* and *archer* conditions, each of which have fully embedded semantically unrelated onset competitors (*tray*, *arch*). The LIFG effects in BA 44/45, which are consistently shown by the inflected morphology in this experiment, may reflect activation of the dorsal system, with all words ending in the IRP undergoing decompositional processing.

Derivational complexity, on the other hand, does not strongly activate the left-lateralised decompositional system associated with BA 44/45. Our previous results suggested that the processing of derived words primarily reflects the general processing demands associated with accessing whole-word lexical representations and the difficulty in separating these from competing alternatives, albeit modulated by the semantic and linguistic transparency of derived words. The current results are broadly consistent with this, showing increased left-lateralised activation primarily in the ventral processing stream, argued to be more related to semantic processes and mapping from sound to meaning. The same pattern held for all three sets of derived words in the current experiment (with the additional small marginally significant effect in dorsal LIFG for the *bravely* set, which requires validation in future research).

Pulling this evidence together points to a consistent picture of the processing and representation of morphologically complex inflected and derived words in English, and the extent to which this is influenced by their underlying morphological structure. The neuroimaging data suggest a differentiation between the two sets of complex words, consistent with reports of dissociations between inflectional and derivational processing in patients with left perisylvian damage (e.g., Hamilton & Coslett, 2007; Tyler & Cobb, 1987). Regular inflected forms are processed and represented compositionally, while derived

forms appear to be processed and represented as full forms (though the structure of these representations may still be modulated by their semantic and linguistic transparency). This may reflect differences in the functional roles played by inflectional and derivational morphemes. Finally, these data highlight the value of a neuro-cognitive framework for understanding and differentiating the mechanisms of language comprehension.

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**Appendix:
Test stimuli**

	PLAYED	TRADE	TREND	BRAVELY	ARCHER	BLEMISH
1	bashed	bald	bind	bomber	adder	amber
2	blamed	bead	bird	bravely	archer	anguish
3	blared	beard	bleed	brewer	army	brother
4	blurred	brand	blend	brightly	awful	cancer
5	blushed	card	blind	chilly	badger	chamber
6	boiled	chest	bond	cleaner	banner	cherish
7	bowed	cleft	breed	climber	beaker	clatter
8	cared	crest	bride	dancer	belly	clever
9	chewed	crude	broad	darkness	bitter	cluster
10	creaked	deft	cloud	densely	blazer	clutter
11	cried	fade	code	dimly	bloomer	danger
12	dared	fast	creed	diver	broker	daughter
13	fried	feed	crust	doubtful	bully	dizzy
14	glared	fend	deed	drinker	bunker	feather
15	gleamed	feud	fiend	drummer	butcher	finger
16	hurled	fold	fist	farmer	corner	flutter
17	jeered	fund	fraud	fiercely	county	folly
18	joined	gold	frost	foolish	fairy	foster
19	kicked	grade	ghost	freakish	finish	furnish
20	laid	graft	grind	freezer	flatter	garnish
21	mashed	grand	guard	freshly	grateful	gender
22	melted	guide	hard	golfer	gully	glitter
23	plucked	hide	hound	guilty	hammer	jolly
24	poured	jade	lard	herbal	jetty	lavish
25	prayed	mild	lend	hunter	ladder	lorry
26	purred	mould	loud	joyful	ledger	monster
27	pushed	proud	nest	loudly	lofty	nourish
28	roared	raid	pond	painful	master	oyster
29	rolled	rend	rind	painter	petty	parish
30	ruined	ride	shade	printer	porter	perish
31	rushed	shrewd	shield	quickly	rafter	plaster
32	sailed	slide	shift	rudeness	rubbish	plunder
33	saved	tend	shroud	safety	saucer	prosper
34	shared	trade	swede	slowly	seedy	quiver
35	sniffed	tuft	third	smoker	silly	rally
36	stirred	tweed	vest	steeply	study	slender
37	thawed	wand	void	sweetness	summer	stammer
38	warned	ward	wound	teacher	treaty	thunder
39	washed	weird	yard	witty	unity	weather
40	yawned	wind	yield	wrestler	vanish	whisper