How the brain composes morphemes into meaning

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Abstract

Morphemes (e.g. [tune], [-ful], [-ly]) are the basic blocks with which complex meaning is built. Here I explore the critical role that morpho-syntactic rules play in forming the meaning of morphologically complex words, from two primary standpoints: i) how semantically rich stem morphemes (e.g. explode, bake, post) combine with syntactic operators (e.g. -ion, -er, -age) to output a semantically predictable result; ii) how this process can be understood in terms of mathematical operations, easily allowing the brain to generate representations of novel morphemes and comprehend novel words. With these ideas in mind, I offer a model of morphological processing that incorporates semantic and morpho-syntactic operations in service to meaning composition, and discuss how such a model could be implemented in the human brain.

Keywords: Morpho-syntax, Semantic composition, Neurolinguistics, Natural language processing

1. Introduction

That you are understanding the words on this page; that you can understand me still, when I talk to you in a noisy pub or over the telephone; that you and I are able to use language to communicate at all, usually effortlessly, exemplifies one of the most critical cognitive faculties belonging to human beings. Here we will focus on a specific aspect of this process; namely how the brain derives the meaning of a word from a sequence of morphemes (e.g. [dis][appear][ed])[1].

[1] There is still some contention as to whether morphemes are neurally represented. An alternative possibility is that lexical information is represented in terms of whole words: the units that would orthographically be flanked by white space Giraudo and Grainger (2000), Devlin et al. (2004). However, given i) the substantial behavioural and neurophysiological evidence that morphemes are in fact represented (for reviews see Rastle and Davis (2008), Amenta and Crepaldi (2012)); ii) the advantage morphological representations provide to speech and text recognition systems (Creutz and Lagus, 2005, Luong et al., 2013, Snyder and Barzilay, 2008, Bojanowski et al., 2017)); iii) the need to move the discussion forward, I take for granted that in representing lexical information, the brain does indeed encode morphological units, likely in combination with, but possibly instead of, morphologically-complex wholes (Marantz, 2013).

A morpheme is defined as the smallest linguistic unit that can bear meaning. The kind of meaning that it encodes depends on what type of morpheme it is. For instance, *lexical morphemes* primarily encode semantic information (e.g. [house], [dog], [appear]); *functional morphemes* primarily encode grammatical or morpho-syntactic information (e.g. [-s], [-ion], [dis-]), such as tense, number and word class. In English, these usually map to root and affix units, respectively, though this differs considerably cross-linguistically. Each morpheme is an atomic element, groups of which are combined in order to form morphologically complex words. For example, to express the process *appear* in the past, one can combine the stem morpheme with the inflectional suffix *-ed* to create *appeared*; to convey the opposite, add a negating prefix: *disappeared.*

In what follows, I will first overview what I consider to be the main neural processing stages supporting morphological processing. In many senses, the selection and description of these stages builds from previous models of behavioural data, such as Schreuder and Baayen (1995), updated to incorporate results from neurolinguistics and natural language processing (NLP). For each processing stage, I will review the relevant literature regarding language comprehension and production.

As should become clear from this review, there are a number of aspects of morphological processing which remain highly under-specified. The goal of the second part of this paper, therefore, is to put forward a composite model of morphological processing, with the aim of offering directions to guide future research. I am as explicit as possible regarding the semantic and morpho-syntactic features at play, the transformations applied at each stage, and where in the brain these processes may be happening. In this sense, then, the discussion will focus on the representational and algorithmic level of analysis, as defined by David Marr (Marr, 1982).

2. Overview of processing stages

In the case of language comprehension, the job of the language listener is to undo the work of the speaker, and reconstruct the intended meaning from the produced expression – to understand the concept *disappeared* rather than to articulate it (Halle and Stevens, 1962, Bever and Poeppel, 2010, Poeppel and Monahan, 2011). I propose that, to achieve this, the following processing stages are involved:

1. **Segmentation**: Identify which atomic units are present.
2. **Look-up**: Connect each of those units with a set of semantic and/or syntactic features.
3. **Composition**: Following the morpho-syntactic rules of the language, combine those features to form a complex representation.
4. **Update**: Based on the success of the *sentence* structure, adjust the atomic representations and combinatory rules for next time.

Note that these operations need not unfold under a strictly serial sequence, such that the previous stage completes before the next is initiated. Rather, based on previous work, it is likely that operations unfold under a more cascaded architecture, such that many computations occur in parallel (e.g. see Gwilliams et al. (2018)). The rest of this section will review the neural evidence in favour of these stages.

2.1. Morphological segmentation: Identifying the building blocks

One of the earliest neural processes is morphological segmentation. The goal is to locate the morphological constituents (roots, derivational and inflectional affixes – defined fully below) within the written or spoken input, and link them to a modality-specific representation (sometimes referred to as a form-based "lexeme"[2] (Laudanna et al., 1992, Caramazza, 1997)).

Evidence for morphological segmentation comes from both written and spoken language processing. Putative anatomical locations for these processes are presented in Figure 1.

Written word processing. During reading, it appears that the brain segments written words into morphemes based on an automatic morpho-orthographic parser (Rastle et al. (2004), McCormick et al. (2008), Crepaldi et al. (2010), Lavric et al. (2012), among others). Whenever both a valid root (either free or bound) and a valid suffix are present in the input, the parser is recruited (e.g. *farm-er, post-age, explode-ion*) (Taft, 1979)). This is true even for words like *vulner-able, excurs-ion* whose stems never occur in any other stem-affix combination (Gwilliams and Marantz, 2018). At this stage, the system is not yet sensitive to the semantic relatedness between the stem and the complex form. This has been shown to lead to false parses of mono-morphemic words like *corn-er* and *broth-er*; the parser is not fooled, however, when a stem is present without a valid affix (e.g. *broth-el*) (Rastle et al., 2004)). Overall, this suggests that the system segments input based on the semantically-blind identification of morphemes that contain an entry in the lexicon.

Visual morpheme decomposition has been associated with activity in the fusiform gyrus using fMRI (Gold and Rastle, 2007), overlapping with the putative visual word form area (Cohen et al., 2002, McCandliss et al., 2003). Corroborating evidence from MEG has also associated this area with morphological segmentation: Responses in posterior fusiform gyrus around 130 ms after visual presentation are modulated by bi-gram and orthographic affix frequency (Pammer et al., 2004, Simon et al., 2012, Gwilliams et al., 2016). This is consistent with the research focused on orthographic processing, which associates this area with the identification of recurring substrings (Dehaene et al., 2005, Binder et al., 2006, Vinckier et al., 2007). Slightly more anterior along the

[2] A lexeme relates to all inflected forms of a morpheme: play, plays, played, playing would all be grouped under the lexeme *play*.

fusiform, responses around 170 ms are modulated by morpheme-specific properties such as stem frequency, affix frequency and the frequency with which those units combine (i.e. *transition probability*) (Solomyak and Marantz, 2010, Lewis et al., 2011, Fruchter and Marantz, 2015, Gwilliams and Marantz, 2018). Anterior fusiform gyrus is therefore associated with decomposing written input into morphemes.

Table 1 summarises these different metrics of orthographic and morphological structure, and specifies the cognitive process they putatively tap into.

Spoken word processing. Less research has been conducted on morphological segmentation of spoken language. Evidence from speech segmentation in general suggests that words and syllables are identified using statistical phonotactic regularities (Saffran et al., 1996), acoustic cues such as co-articulation and word stress (Cutler and Butterfield, 1992, Johnson and Jusczyk, 2001) and lexical information (Mattys et al., 2005). Similar kinds of statistical cues appear to be used for morpheme boundaries as well. In particular, there is sensitivity to the transition probability between spoken morphemes (Ettinger et al., 2014, Gwilliams and Marantz, 2015) in superior temporal gyrus (STG) at around

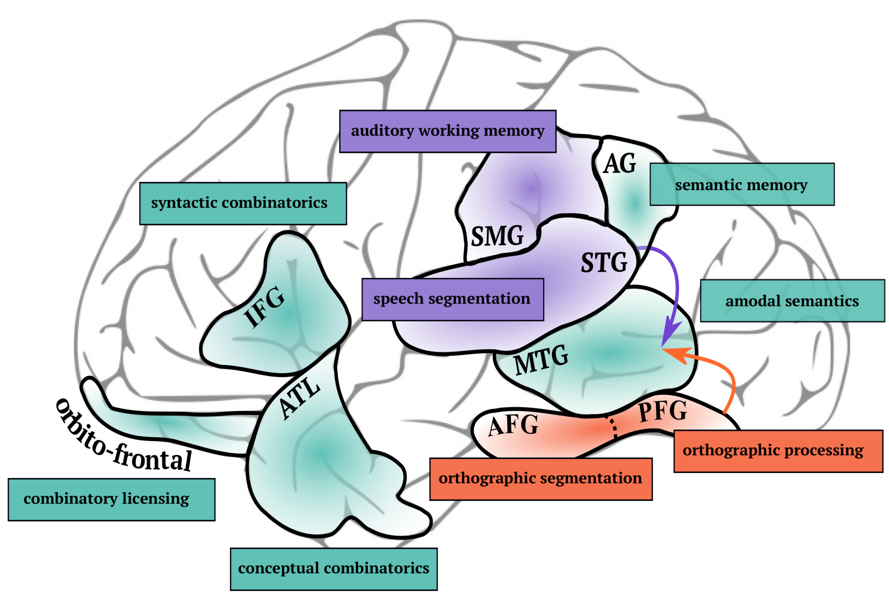

Figure 1: **Putative brain regions associated with different stages of morphological processing.** Orange colour refers to modality-specific written word processes. Purple colour to modality-specific spoken word processes. Turquoise refers to a-modal processes. PFG: posterior fusiform gyrus; AFG: anterior fusiform gyrus; STG: superior temporal gyrus; SMG: supramarginal gyrus; AG: angular gyrus; MTG: middle temporal gyrus; ATL: anterior temporal lobe; IFG: inferior frontal gyrus.

Feature	Formula	Process, Timing	Example study
Bigram frequency	$\log \sum(a, b)$	Orthographic, 130 ms	Simon et al. (2012)
Stem frequency	$\log \sum(X)$	Segmentation, 170 ms	Gwilliams et al. (2016)
Affix frequency	$\log \sum(Y)$	Segmentation, 170 ms	Solomyak and Marantz (2010)
Transition probability	$P(Y\|X)$	Segmentation, 170 ms	Gwilliams and Marantz (2018)
Base frequency	$\log \sum(X)$	Lexical access, 350 ms	Lewis et al. (2011)
Family entropy	$-\sum(P(W\|C) \log_2 P(W\|C)$	Lexical access, 350 ms	del Prado Martın et al. (2004)
Semantic coherence	$E(freq(W)) - freq(X + Y)$	Composition, 400-500 ms	Fruchter and Marantz (2015)

Table 1: **Summary of experimental variables** that have been used to tap into different stages of morphological processing. Here, (a, b) = letters of the input; (X) = stem; (Y) = affix; (W) = morphologically complex word; (C) = cohort of morphologically related words; E = expected value

200 ms after phoneme onset. These moments of low transition probability may be used as boundary cues to bind phonological sequences into morphological constituents.

For both auditory and visual input, then, the system applies a morphological parser on the input, which segments the signal based on sensory (pitch, intensity, bigrams), form-based (identification of affix or stem string), and statistical information (transition probability).

2.2. Lexical access: Figuring out what the blocks mean

Identifying the meaning of the segmented morphemes is often referred to as "lexical access". This stage involves linking the form-based morpheme to the relevant bundle of semantic and syntactic features. Each word consists of at least three pieces: the root, (any number of) derivation(s) and inflection, even if one of the pieces is not spelled out in the written or spoken language (Pesetsky, 1996). Depending on the type of morpheme being processed, the features are different.

2.2.1. Root access

Root morphemes are the smallest atomic elements that carry semantic properties; units like: *house, dog, walk, love.* Based on previous theoretical work (e.g. Embick and Marantz (2008)), the root is assumed to not yet be specified for its word class; so, the use of *love* as a verb (*to love*) and a noun (*the love*) contains the same root morpheme.

The middle temporal gyrus (MTG) has been implicated in semantic lexical access in a number of processing models (Indefrey and Levelt, 2004, Hickok and Poeppel, 2007, Friederici, 2012), along with the superior temporal sulcus (Binder et al., 2000). The angular gyrus has also been implicated in semantic memory more broadly (see Binder et al. (2009), Binder and Desai (2011), Binder et al. (2016) for a review of anatomical locations associated with semantic processing).

A particular response component found in MEG, whose neural source originates from MTG at around 350 ms after word onset, has been associated specifically with access to the decomposed *root* of the whole word (Pylkkänen et al., 2004, 2006, Fiorentino and Poeppel, 2007). This has been corroborated by the finding that neural activity in this area, at this latency, is modulated by lemma frequency (Solomyak and Marantz, 2010), polysemy (Pylkkänen et al., 2006) and morphological family entropy (Pylkkänen et al., 2004, Fruchter and Marantz, 2015) - perhaps reflecting competition between the recognition of different roots.

2.2.2. Derivation access

Derivational morphology refers to a constituent (e.g. *-ion, -ness, -ly*) that creates a new lexeme from that to which it attaches. It typically does this by changing part of speech (e.g. employ → employment), by adding substantial non-grammatical meaning (e.g. child → childhood; friend → friendship), or both (Anderson, 1985).

There are data from cross-modal priming studies indicating that derivational suffixes can be primed from one word to another (darkNESS - happiNESS) (Marslen-Wilson et al., 1996). This suggests that i) there is an amodal representation (i.e. not bound to the visual or auditory sensory modalities) that can be accessed and therefore primed during comprehension; ii) the representation is somewhat stable in order to generalise across lexical contexts. Furthermore, findings from fMRI link the processing of derived forms with activity in the LIFG (Carota et al., 2016) – i.e. *Broca's area*, which is traditionally associated with syntactic processing, broadly construed. This region has also been associated with the processing of verbal argument structure (Thompson et al., 2007), further implicating the LIFG in derivational morphology, though, overall, the processing of derivation is not as clear as it is for roots (Leminen et al., 2018).

2.2.3. Inflection access

Inflectional morphology invokes no change in word class or semantic features of the stem. Instead, it specifies the grammatical characteristics that are obliged by the given syntactic category (Anderson, 1985). In English, inflectional morphemes would be units like *-s, -ed, -ing.*

Similar to derivational morphology, and with more empirical support, inflectional morpho-syntactic properties appear to be processed in the left inferior frontal gyrus (LIFG) (Marslen-Wilson and Tyler, 2007, Whiting et al., 2014). This area is recruited for both overt and covert morphology (i.e. inflections that are realised with a suffix (ten lamb + s) and those that are silent (ten sheep + ∅) (Sahin et al., 2009)), which suggests that the same processing mechanisms are recruited even when the morphology is not realised phonetically or orthographically.

2.3. Morphological combination: Putting the blocks together

In order to comprehend the meaning of the complex item, the system needs to put together the semantic and syntactic content of the constituents. This is referred to as the *composition* stage of processing.

The majority of work morphological composition has employed quite coarse categorical distinctions between semantically valid and invalid combinations. For example, morphologically valid combinations like *farm+er* elicit a stronger

EEG response at around 400-500 ms as compared to invalid combinations like *corn+er* (Dominguez et al., 2004, Morris et al., 2007, 2008, Lavric et al., 2011, 2012). MEG work has associated this with activity in the orbito-frontal cortex (Pylkkänen and McElree, 2007, Pylkkänen et al., 2009, Fruchter and Marantz, 2015, Neophytou et al., 2018).

In a slightly more fine-grained comparison, Fruchter and Marantz (2015) tested just morphologically valid combinations, and found how expected the meaning of the whole word is from its parts (termed "semantic coherence") also drives orbito-frontal activity at around 400 ms. This has been interpreted as reflecting a stage that assesses the compatibility between the composed complex representation and the predicted representation given the parts of the word. Broadly though, the mechanism by which morphemes are combined is extremely under-specified, and is a rich avenue for future study.

3. Composite model of morphological processing

The discussion so far has reviewed literature regarding three stages of morphological processing. While neuro-biological research provides quite a comprehensive explanation of how the brain segments sensory input into morphological constituents, our understanding remains poorly defined in terms of i) what linguistic features make up the representation of each morphological unit; ii) what operations are applied to those features at each stage of composition. Therefore, the rest of this article is dedicated to putting forward a framework that is explicit on both of these points, in order to guide future studies. It is informed by the neural data reported above, and insights from linguistics and natural language processing (NLP).

3.1. Morpheme segmentation

It is interesting to note that the neurophsyiological findings regarding morphological decomposition are echoed in the engineering solutions developed in NLP. Some tools employ a storage "dictionary" of morphological constituents that are compared to the input to derive units from the speech or text stream (Qiu et al., 2014). This is similar to the stem+affix look-up approach of Taft (1979). Other morphological segmentation tools such as *Morfessor* work by picking up on statistical regularities in the input and maximising the likelihood of the parse in a unsupervised manner (Creutz et al., 2007). This is related to sensitivity to grapheme and phoneme transition probability as attested in the posterior fusiform and superior temporal gyrus, respectively. Overall, both types of NLP segmentation – dictionary lookup and statistical regularity – are attested in the cognitive neuroscience literature as methods the brain uses for segmentation.

3.2. Morpheme representations

The framework presented here treats morphemes (and words) as a set of semantic and syntactic features. Figure 2 visualises a collection of some example features for four words.

Computationally, this means that each morpheme is represented as a list of numbers. Each slot in the list corresponds to a particular feature (e.g. *cute, loud, plural*), and the number associated with that slot reflects how relevant a feature is for that morpheme. The list of numbers that represents each morpheme, or each word, is henceforth referred to as a *vector*.

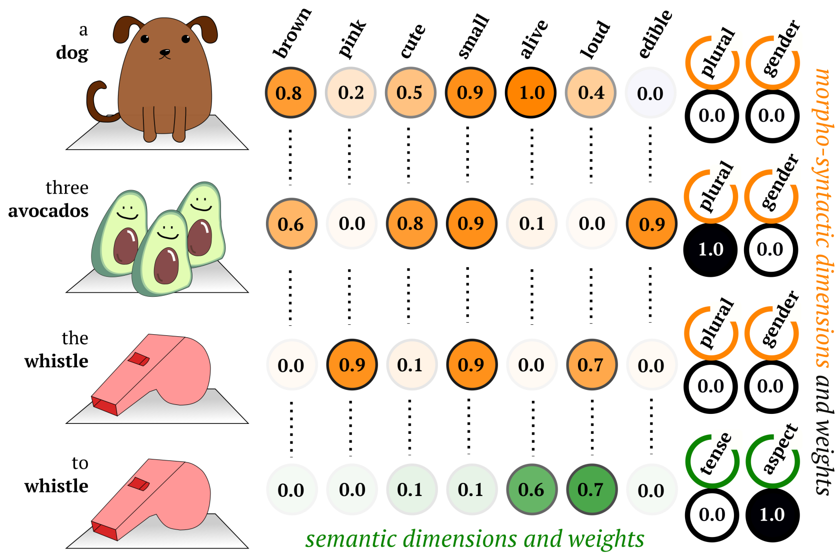

Figure 2: **Representing words as vectors.** For the three morphologically composed words *dog, avocados, whistle*, the semantic and syntactic features are displayed. The first seven features refer to the semantics of the item; the last two features refer to syntactic properties. The labelled disks correspond to the morpho-syntactic dimensions that are relevant to the word, as primarily provided by the derivation; the weights of those dimensions is specified by the inflection, as shown in greyscale. Each word is expressed under the same set of semantic dimensions, but the syntactic dimensions differ depending on the word class of the item. The orange colour denotes that this item is a noun; the green colour: a verb.

Precisely how many semantic dimensions define a word is likely impossible to answer. But, I propose that all words are defined relative to the same set of semantic features, and the feature-slot correspondence is the same across all words. This systematicity between the index of the vector, and the meaning of that dimension, is what allows the brain to keep track of what elements contain what information, and apply the appropriate computation.

In terms of neural implementation, each dimension of the vector could be realised by a neuron or neuronal population that codes for a particular feature. The vector format has been chosen for modelling purposes because it supports basic mathematical operations; but, the vector format itself is not critical for how these processes work in the brain.

Root features. The root morpheme is proposed to consist only of semantic properties. The root in *dogs* for example, is *dog*, which may have a feature for *brown, fluffy, cute, small, mammal* and *barks.* The root itself is assumed to not be associated with any particular word class - this is only determined once it is combined with derivational morphology, as explained below. So, in its acategorical form, I hypothesise that the weights for each feature correspond to the average weight given all the contexts of use of the word.

In NLP, the meaning of words are routinely represented as *semantic word embeddings* (e.g. Creutz and Lagus (2005), Snyder and Barzilay (2008), Luong et al. (2013), Bojanowski et al. (2017)). These vectors are created based on the co-occurrence of words: capitalising on the fact that words that mean something similar often occur in similar contexts[3]. They provide a powerful way of representing meaning and obey simple geometric transformations (for example, subtracting $\vec{man}$ from $\vec{king}$ and adding $\vec{woman}$ results in a vector that closely approximates $\vec{queen}$ (Pennington et al., 2014)). In these methods, the vectors typically have a dimensionality of 50-300 features, where the features themselves are extracted using unsupervised techniques such as principle component analysis. As a consequence, it is often not possible to assign a meaningful label to each dimension.

I want to highlight that even though this is a highly successful method for solving language engineering problems, I am not proposing that this is how the brain acquires dimensions of understanding. Rather, I believe that the dimensions of word embeddings, as learnt through corpus statistics, are conveniently correlated with the "true" dimensions of meaning used by the brain, thus leading to their correlation with neural activity (Huth et al., 2016). Determining what those "true" features are, though, will likely require more manual inspection and human intuition (e.g. along the lines of Binder et al. (2016).

Derivation features. Unlike the potentially infinite number of semantic features, syntactic features are of a closed finite set. Given the significant stability of word classes and morpho-syntactic features cross-linguistically, I propose that the derivation contains a place-holder for all possible morpho-syntactic properties of the particular syntactic category (Cinque, 2006). So, for example, even though English does not mark grammatical gender, a native English speaker would still have a slot for this morpho-syntactic feature in their representation of nouns. This is very much in line with *categorical structure* as proposed by Lieber (1992). For example, the morpheme *-ful*, which derives an adjective from a noun, would contain adjectival morpho-syntactic features such as *function, complementation, gradation.* The suffix *-ion* contains nominal features such as *case, number, gender.* The suffix *-ify* contains verbal features such as *tense, aspect, mood.* The index location of these morpho-syntactic features would also always be stable within the representation of the whole word (so, which entry

[3]This is highly consistent with the *Distributional Hypothesis* of semantics – a prevalent usage-based theory of word meaning (Harris, 1954, Firth, 1957).

in the vector, for the computational implementation; which feature-sensitive neuron(s), for the neural implementation). This way, the system knows from where to extract the derivational dimensions, and on what features to apply the relevant compositional functions.

Critically, the derivation only serves to specify which morpho-syntactic features are of potential relevance. It does not actually contain the weights for each dimension – that is the job of the inflection, as expanded upon below. In this way, then, the derivation acts as a kind of co-ordinate frame: it determines the word-class of the whole word by specifying the relevant syntactic dimensions that it should be expressed within. In Figure 3, the co-ordinate frame is depicted by the colour of the vector.

I propose that the derivation is also specified in terms of the same semantic dimensions that define the root morpheme. For example, this semantic feature would be shared between child*hood*, man*hood* and woman*hood*; and between charm*er*, kiss*er* and walk*er*. Furthermore, there may also be semantic similarities within word classes more generally, either expressed as an explicit feature, or as an emergent property of occupying similar syntactic roles. For example, the semantic noun-y-ness associated with *mountain* may be shared with the noun-y-ness of *petrol*.

Inflection features. I propose that the inflectional morpheme serves to specify the value for each of the morpho-syntactic dimensions identified by the derivation. For example, if the derivation recognises *number* as a relevant dimension for the stem, it is the inflection that specifies whether the word is singular or plural. If the derivation specifies a feature that is not applicable to the word being processed, such as *gender* for the English word *table*, then the inflection simply allocates a zero weight. This is consistent with Levelt et al. (1999)'s lexical access model of speech production.

3.3. Compositional computations

Now we move to a critical aspect of morphological processing, which is how the morphemes are combined in order to form a complex meaning. The basic proposal here is that the three types of morphemes obey three types of combinatoric operations, which unfold in a particular order, and with predictable consequences on the semantic and syntactic outcome of the word. Below, each combinatorial stage of processing is explained in turn.

Concatenation and multiplication to create the stem morpheme. The first operation involves combining the semantics of the root morpheme (purple vector in Figure 3, step 1) with morpho-syntactic dimensions of the initial derivation (step 2). This forms the stem morpheme, which is specified for its word class (step 3) (Embick and Marantz, 2008).

Computationally, I propose that this involves two steps. One is concatenating the syntactic dimensions that are of potential relevance given the word-class of the derivation to the representation of the root morpheme. Second is modulating the semantic features of the root, relative to the word-class of the

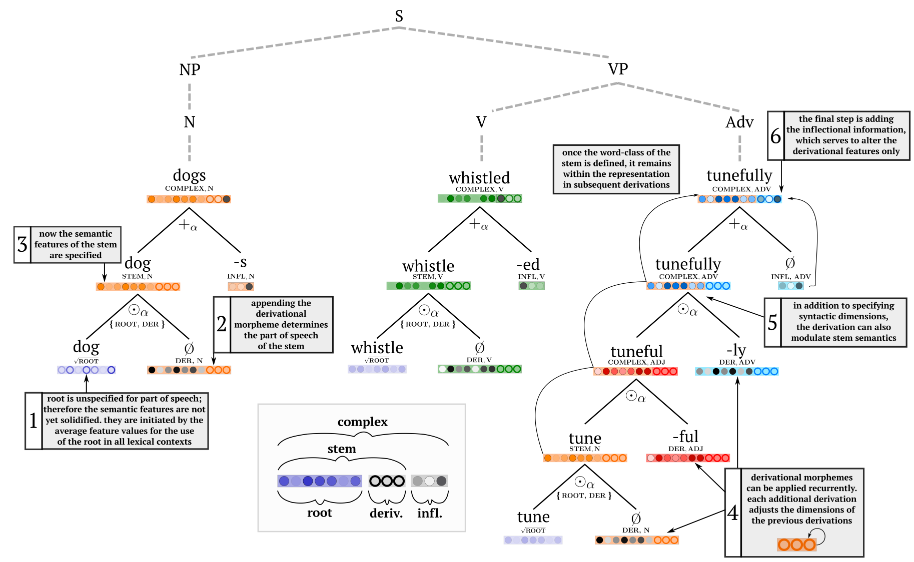

Figure 3: **Morpho-syntactic composition.** Detailing the morphological composition recruited during the processing of the sentence *dogs whistled tunefully*. The colour specifies the word-class of the unit (purple: acategorical; orange: nominal; green: verbal; red: adjectival; blue: adverbial). The index of the feature in the vector is what determines its semantic/syntactic function. $\varnothing$: a morpheme with no phonological or orthographic realisation; { ROOT, DER }: concatenation of vectors; $\odot$: element-wise multiplication; $+$: addition; α: learnt combinatorial weight. This allows the modulation of the semantic features to be adjusted with experience with a particular language. I am assuming, in line with linguistic theories (Halle and Marantz, 1994, Harley and Noyer, 1999, Halle and Marantz, 2004), that the root is unspecified for word class (e.g. adjective, noun, verb).

derivation. This second procedure can be achieved through element-wise multiplication, such that the derivation systematically increases the weight of certain dimensions, and decreases the weight of others. This forms a stem morpheme, whose semantic and syntactic properties are defined relative to its established word class. An explicit example of this process is shown in Table 2.

Multiplication at each derivation. After this initial stem-formation stage, any number of additional derivational operations can then be applied (step 4 in Figure 3). Each additional transformation involves adjusting which morpho-syntactic dimensions are relevant, and at the same time, modulating the semantic dimensions in line with the syntactic category. For example, if transforming a noun into a verb, the relevant syntactic dimensions change from *number* and *gender* to *tense* and *aspect*. Further, the semantic dimensions change from highlighting visual aspects of the concept to kinetic aspects of the concept.

In line with this idea, behavioural studies have shown that listeners are sensitive to the word class of the stem, even when the word as a whole ends up

	Whistle (Root)		∅ (Verbal)		**Whistle** (Stem)		**-er** (Nominal)		**Whistler** (Complex Noun)		**-s** (Inflection)		**Whistlers** (Inflected)
Sound	0.9		1.0		0.9		1.0		0.9		∅		0.9
Social	0.3		0.8		0.24		5.0		1.2		∅		1.2
Shape	0.5	$\odot$	0.2	=	0.1	$\odot$	0.5	=	0.05	+	∅	=	0.05
Happy	0.5		2.0		1.0		1.0		1.0		∅		1.0
Human	0.2		0.3		0.06		10.0		0.6		∅		0.6
	∅		Tense		Tense		Plural		Plural		1		1
	∅		Aspect		Aspect		Gender		Gender		0		0

Table 2: **Mathematical example** of the derivational processes leading to the formation of the complex word *whistler*. $\odot$ refers to element-wise multiplication between vectors. + refers to vector addition. Top part of the table corresponds to semantic dimensions; bottom part to syntactic dimensions. The semantic dimension labels were taken from Binder et al. (2016).

being a different syntactic category (e.g. the verb *explode* in the nominalisation *explosion*) (Gwilliams et al., 2015). This suggests that the history of syntactic dimensions is accessible during comprehension.

Critically, I propose that the semantic consequences on the properties of the word are predictable given knowledge about the semantic input and the syntactic operators being applied. In theory, this means that a derivation will always modulate the features of the root in the same way, and this will generalise across lexical contexts. As expanded upon below, this connection between syntax and meaning is precisely what allows for the comprehension of novel words.

Addition at the inflection. The final stage involves combining the lexical structure with the inflectional morpheme (step 6 in Figure 3). Here I have denoted the combinatorial operation as simple element-wise vector addition (+) between the morpho-syntactic features of the derivation (all of which are zero) and those of the inflection (non-zero). In this way, the inflection works to specify the weights of the derivational suffix, making explicit which morpho-syntactic properties are relevant and to what extent. This is also depicted on the right side of Figure 2.

This idea of vector manipulation, in service to meaning composition, has enjoyed success in previous NLP research. Studies have used morpheme vector representations in a broad sense, though not strictly coding for semantic versus morpho-syntactic properties of the units (Creutz and Lagus, 2005, Luong et al., 2013, Snyder and Barzilay, 2008, Soricut and Och, 2015, Bojanowski et al., 2017). Even when using a simple composition rule such as addition or element-wise multiplication between morpheme vectors (Mitchell and Lapata, 2010), these composed vectors reasonably approximate semantic representations of morphologically complex whole words (Lazaridou et al., 2013, Cotterell and Schütze, 2018). This suggests that implementing even a very basic composition function could serve to generate complex lexical meaning.

Cross-linguistic coverage. As is true for any model of language processing, it is important that it is equally applicable across different languages. Although in English the usual order of morphological units is: root, derivation, inflection, this is not the case for languages with different typologies. For example, some languages make use of infixation: the embedding of an affix *within* a root, rather than before (prefixation) or after (suffixation). Further, Semitic languages, such as Arabic, have dis-continuous morphemes. In this case, the three morphemes are received by the listener in an interleaved fashion, with no neat boundary between one morpheme and the next. For example, in the word *kataba*, the root is expressed as the consonants *k-t-b* and the pattern *-a-a-a* expresses derivational information.

The current proposal predicts that the same basic set of operations (stem formation; derivation; inflection) are always applied, and always in the same order, regardless of the order that the information is received. From this perspective, knowledge of the language-specific grammar is used to organise the input into an appropriate syntactic structure. This then allows that input to be processed under the language-general processing architecture described here. This makes the strong prediction that, regardless of the language being processed, the neural signatures of these processes should always occur in the same order.

3.4. Feedback from the sentence structure

Once the full sentence structure has been created, the sentence can similarly be represented in terms of a set of semantic and syntactic features. This process - of generating a semantic-syntactic representation of the sentence - is not discussed here, but I point the reader to Baroni et al. (2014) for related ideas of how this may be achieved. In abstract, the idea is that the sentence representation is built using similar compositional rules to those currently described, as well as additional non-structural meaning as derived from the broader situational and pragmatic context.

The final part of the current framework is the idea that the system can utilise this sentence structure to inform morphological structure in two ways: i) *update* or strengthen the constituent representations; ii) *create* representations of novel morphemes.

Update. Once the sentence is built, this can be used to compute the most likely representations of morphological constituents given the semantic content and syntactic structure of the sentence. One possible mathematical implementation of this would be Bayesian inference, where the most likely meaning of $\mathrm{morpheme_j}$ is inferred based on the representation of the sentence as computed without $\mathrm{morpheme_j}$:

$$P(\vec{morpheme_j}|\vec{sentence_{-j}}) \propto P(\vec{sentence_{-j}}|\vec{morpheme_j}) \times P(\vec{morpheme_j}) \tag{1}$$

The discrepancy between the inferred morpheme (the posterior), and the constituent representation (the prior), can be thought of as the representational error:

$$\vec{error} = P(\vec{morpheme_j}) - P(\vec{morpheme_j}|\vec{sentence_{-j}}) \tag{2}$$

If the sentence structure has low semantic or syntactic validity, the error will be high, which can be used as a feedback signal in order to update the constituent representation. This will improve validity for next time, by making the morpheme representation more similar to the inferred posterior representation given the sentence structure. Whereas if error is low, the signal will simply strengthen the prior representations that are already in place.

One obvious prediction borne out of this model is that the *update* process would have most influence during language acquisition, while lexical representations are still in the process of being formed. An interesting avenue for further study would be to test how neural correlates of representational updates correspond to behavioural improvements in comprehension and production.

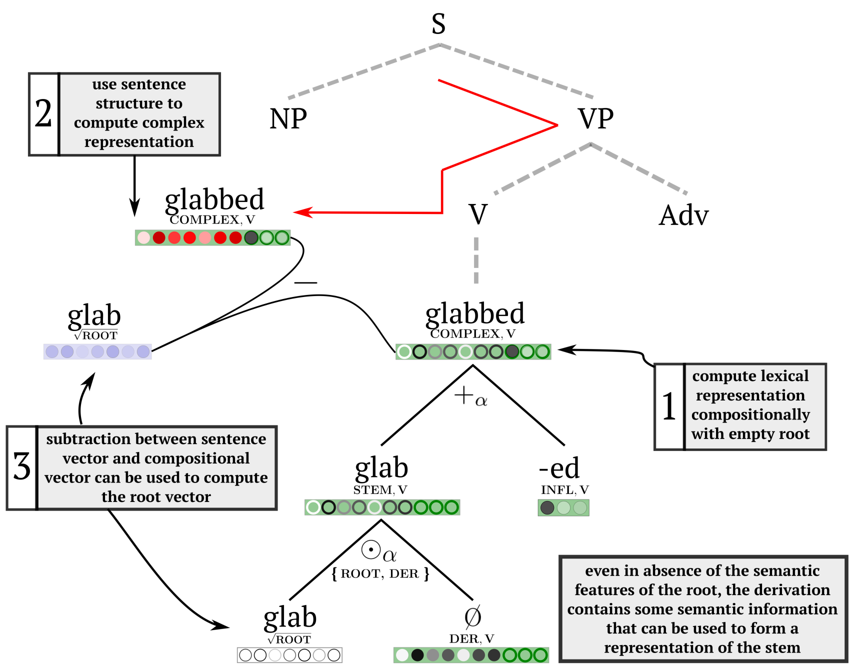

Figure 4: **Using sentence structure and morphological rules to generate representations.** The meaning of the novel word *glabbed* can be estimated using the meaning of the sentence structure (similar to jabberwocky sentences). From there, the meaning of all atomic elements are also generated, by performing simple mathematical operations on the known representations.

Create. Given that the proposal here is that the brain primarily conducts language processing via the atomic morphological units, it is critical that it ensures full coverage over those units. When encountering a morpheme for the first time, the sentence structure can be used to generate the required constituent representations. This idea is quite similar to *syntactic bootstrapping* – using structural syntactic knowledge to understand the semantic content of novel words (Gleitman, 1990, Landau et al., 2009, Lidz et al., 2003). Here I propose this can be achieved by applying the following sequence of operations.

First, the compositional representation of the whole word is computed (step 1 in Figure 4). The derivational and inflectional morphology are defined in line with the user's knowledge of the language, but because the word has not been encountered before, the root contains null entries. As shown in equation (3), the composed meaning of the novel word *glabbed* can be computed as:

$$\vec{glabbed}_{\text{composition}} = \vec{\varnothing} \odot \vec{DER}_V + \vec{INFL}_V \tag{3}$$

Because the composition has been applied using an empty root, the resulting representation only reflects the morpho-syntactic and semantic properties of the affixes.

Second, the whole-word representation can be estimated from the sentence context, using the same Bayesian method as described above (and step 2 in Figure 4):

$$\vec{glabbed}_{\text{sentence}} = P(glabbed|sentence) \tag{4}$$

Third, a subtraction between the composed meaning of the word as computed with a null root, and the interpreted meaning of the word given the sentence can be used to interpolate an atomic representation of the root (step 3 in Figure 4):

$$\vec{glab}_{\text{new}} \ = \vec{glabbed}_{\text{sentence}} - \vec{glabbed}_{\text{composition}} \tag{5}$$

This interpolation process may serve to "initialise" the representation of a root vector. Then, at each subsequent use, the error computed as compared to the morphological representation from the sentence can be used to update that representation using the method described above.

Again, while this process is most obviously recruited during language learning, the same mechanism is hypothesised to still be in effect in proficient speakers. Every time a listener is faced with a morphologically complex word, all of the atomic constituents of that word can be computed through an iterative subtraction of affixes. This makes the prediction that the system will hold representations of constituents that are never encountered in isolation: for example, of the root *excurse* from *excursion*. Recent evidence from MEG suggests that this is indeed the case (Gwilliams and Marantz, 2018).

Filling gaps in the lexicon through either interpolation of constituents, or combination into complex forms, is precisely the main advantage owed to morphological over word-based representations in NLP. The use of vector representations of morphemes provides better predictive power, especially for out-of-vocabulary words that do not exist in corpora (Creutz and Lagus, 2005, Luong et al., 2013, Snyder and Barzilay, 2008, Bojanowski et al., 2017).

Overall, this highlights that the systematicity between structure and meaning provides a powerful framework for generating missing semantic representations based on the syntactic (both lexical and sentential) situation alone. In this way, it is plausible that the language faculty *in general* is primed to associate syntactic information with particular semantic information. As discussed, this has clear advantages for language acquisition, along the lines of syntactic bootstrapping, as the process of meaning generation would be employed every time a new word is encountered.

Taking this idea one step further, one can imagine that not only the representation is computed, but also a relative activation strength of that representation. Typically, the activation level of a word is thought to be a consequence of how often that word is retrieved from the lexicon: frequent words are accessed more often and therefore have a higher activation level. An alternative explanation is that the system *wants* to make frequently accessed words easier to recognise, and so keeps them activated. From this perspective, activation level would be based on the statistical properties of the word - its orthographic, phonological, morphological structure - rather than (or independently from) frequency of exposure and age of acquisition (Gerhand and Barry, 1998). If this is true, then the activation level of a novel word could be computed based upon those regularities, and how active a word is may be reflected in the *magnitude* of the corresponding vector representation.

To my knowledge, this has not yet been tested, but would be easy to do. Although it is a simple distinction, whether word frequency effects are a *consequence* of lexical access or a *engineered processing advantage* has sizeable consequences on the structure of language process and of the mental lexicon more generally.

4. Discussion

The goal of this paper is to offer a model of morphological composition that makes explicit i) what linguistic features make up the representation of a morphological unit; ii) what operations are applied to those features. While the proposal is based as much as possible on extant literature, it also includes some untested, but testable, educated guesses. There are a number of aspects of morphological processing in the brain which remain highly under-specified; therefore, a fruitful avenue for future research will be to explicitly test the predictions of this model with neural data.

For example, each stage of processing is associated with a particular compositional rule: concatenation and multiplication at the first derivation; multiplication at subsequent derivations and addition at the inflection. Further, the proposal suggests these operations are always performed in the same order, regardless of the language being processed. Whether this is indeed the type and order of neural operations needs to be tested, perhaps by testing whether a sequence of intermediate representations are encoded in neural activity before arriving at the final complex representation. It would also be informative to correlate the features of both the simple morpheme vectors and the complex word vectors with neural activity to test whether the input/output sequence as tracked by the brain indeed obeys the mathematical operations outlined here.

Although this article has focused on morphological processing, it is possible that these basic principles hold true across multiple units of language. The most obvious analogy is between the syntactic operations used to generate phrasal structures and those used to generate word structures. In line with linguistic theory (Halle and Marantz, 1994, Harley and Noyer, 1999, Halle and Marantz, 2004), the current proposal makes no meaningful distinction between the two. This is an intuitive idea. For instance, there is very little difference between the composed meaning of *sort of blue* and *blueish*, even though one is made of a phrasal structure and the other a lexical structure. Further, some languages may choose to encode information using multiple words (e.g. *in the house*, English) whereas others may use multiple morphemes (e.g. *extean*, Basque). That one contains orthographic spaces and the other does not is quite arbitrary, and it is not clear whether there are any meaningful processing differences (Moro et al., 2001), above and beyond things like differences in unit size (Ullman, 2004). Indeed, morphologically rich languages, such as Ojibwe, allow a very large number of morphemes to be combined, which form a sentence structure that essentially only consists of a single word. In such cases, it is hard to draw a meaningful distinction between the structure of morphemes to make words, and the structure of words to make sentences.

Overall, this work shows that combining insight from NLP, linguistics and cognitive neuroscience to develop hypotheses for biological systems is potentially very powerful, as each field is essentially tackling the same problem from differing standpoints. For example, in NLP, the goal is to engineer a system to achieve language comprehension with (at least) human-level ability; for neuroscience, the goal is to understand the system that has already done that: the human brain. Consequently, each field has developed tools and insights that (perhaps with a bit of tweaking in implementation or terminology) are mutually beneficial.

5. Conclusion

Composition of morphological units provides insight into the infinite potential of meaning expression, and the critical systematicity between syntactic structure and semantic consequence. Here I have briefly reviewed research across cognitive neuroscience, linguistics and natural language processing in order to put forward a model of morphological processing in the human brain. I hope that this serves as a useful overview, and highlights fruitful avenues for further discovery.

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