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The neural bases of the learning and generalization of morphological inflection

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ABSTRACT

Affixal inflectional morphology has been intensively examined as a model of productive aspects of language. Nevertheless, little is known about the neurocognition of the learning and generalization of affixal inflection, or the influence of certain factors that may affect these processes. In an event-related fMRI study, we examined the neurocognition of the learning and generalization of plural inflections in an artificial language, as well as the influence of both affix type frequency (the proportion of words receiving a given affix) and affix predictability (based on phonological cues in the stem). Adult participants were trained in three sessions, and were scanned after the first and last sessions while inflecting trained and untrained words. Untrained words yielded more activation than trained words in medial frontal (including pre-SMA) and left inferior frontal cortices, which have previously shown activation in compositional grammatical processing. A reliance on phonological cues for untrained word inflection correlated positively with pre-SMA activation, but negatively with activation in the pars triangularis. Thus, pre-SMA may be involved in phonological cue-based composition, while the pars triangularis underlies alternative processes. Inflecting trained items yielded activation in the caudate head bilaterally, only in the first session, consistent with a role for procedural memory in learning grammatical regularities. The medial frontal and left inferior regions activated by untrained items were also activated by trained items, but more weakly than untrained items, with weakest activation for trained-items taking the high-frequency affix. This suggests less involvement of compositional processes for inflecting trained than untrained items, and least of all for trained inflected forms with high-frequency affixes, consistent with the storage of such forms (e.g., in declarative memory). Overall, the findings further elucidate the neural bases of the learning and generalization of affixal morphology, and the roles of affix type frequency and affix phonological predictability in these processes. Moreover, the results support and further specify the declarative/procedural model, in particular in adult language learning.

1. Introduction

Affixal inflectional morphology has often been used as a model for investigating the learning and processing of productive aspects of both first and second language, and their neural bases. Inflectional affixes within a given morphological system tend to vary in the extent of their applicability, based on various factors such as affix type frequency (the proportion of words receiving a given affix; Croft (2007)) and affix predictability (the degree to which the affix can be predicted from phonological or other cues in the stem). Indeed, as we shall see, behavioral evidence suggests that both affix type frequency and affix predictability seem to modulate both the learning and generalization of affixal inflection. However, we are not aware of any previous studies investigating the *neural* bases of the influence of these factors on affixal inflection, or even the neural substrates of learning and generalizing affixal inflection more generally. The current study was designed to address these gaps, with possible broader relevance to other productive aspects of language. Specifically, the aim of this behavioral and fMRI study was to elucidate the neurocognition of the acquisition and generalization of affixal inflection in adults learning an artificial language, in a multi-session training paradigm, while probing the influence of affix type frequency and affix predictability.

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1.1. Behavioral evidence regarding the influence of affix type frequency and affix predictability on affixal inflection

1.1.1. Evidence from natural languages

The influence of both affix type frequency and affix predictability on affixal inflection has been examined in natural language. To date such behavioral research has focused on first language, with little work on second language. Additionally, most such studies have investigated the effects of generalizing inflectional affixes (to novel or irregular forms), with little research probing the effect of these variables on the learning or processing of existing inflected forms.

At least in first language, higher affix type frequency seems to be associated with a greater tendency to generalize inflectional affixes. (We are aware of no work on affix type frequency in second language.) For example, Dabrowska and Szczerbiński (2006) found that 2 and 3 year old children's application of inflectional affixes to nonce words in Polish was positively correlated with the inflectional affixes' frequencies. In other studies, overgeneralization (over-regularization) rates of inflectional affixes to irregulars (e.g., 'goed') seem to correlate with the inflection's affix type frequency, with fairly high rates for the (high affix frequency) regular '–ed' past tense and '–s' plural inflections in English (Maslen et al., 2004), but low rates for the (low affix frequency) '–s' plural inflections in German (Köpcke, 1998).

When words with common semantic or phonological characteristics take the same inflectional affix, these characteristics can act as cues to the affix. The degree to which cues can reliably predict inflectional affixes can vary. The predictability of an inflectional affix, given a cue, can be defined as the proportion of words with the cue that take the affix out of the total number of words containing the cue. In some languages, semantic and phonological cues are correlated. For example, gender serves as a cue for the selection of plural inflectional affixes for Hebrew nouns (-ot vs.-im), and is itself at least partly predictable based on word-final phonemes (Berent et al., 1999; Ravid et al., 2008). In other languages (e.g., plural inflections of German nouns; Laaha, 2011) phonological cues are not correlated with semantic cues, and both types of cues may help predict the correct inflection. Phonological cue predictability has been found to correlate positively with both the learning and generalization of inflectional affixes, in both first and second language. Laaha (2011) found that native German speaking children perform better at producing existing inflected forms that have more predictable plural affixes, suggesting that these forms were better learned. In native speakers greater phonological cue predictability also appears to be associated with a higher generalization rates of inflectional affixes, both to novel forms (Albright and Hayes, 2003) and to irregulars, in the form of over-regularizations (Hartshorne and Ullman, 2006). Note that the examination of phonological predictability for stem-changing irregulars (Pinker, 1991; Pinker and Ullman, 2002) is not discussed here, as we focus on affixal inflection. Finally, higher phonological predictability has been found to improve both the learning and generalization of affixal inflection in second language (Kempe and Brooks, 2008).

1.1.2. Evidence from artificial languages

Although most previous work on the influence of affix type frequency and affix predictability on morphology has, not surprisingly, examined natural language, research has begun to turn to artificial languages to examine these issues. Artificial language paradigms are particularly well suited for examining learning and generalization because one can tightly control the amount and type of language exposure, such as manipulating factors of interest in the input. Artificial linguistic paradigms have the added advantage that, likely because they are small, they can generally be learned to reasonably high proficiency over the course of hours to days, thereby enabling the longitudinal examination of language learning and generalization.

Hence, despite concerns regarding their ecological validity because they do not reflect the full complexity of natural languages, artificial languages have been widely used in the investigation of both vocabulary (Tamminen et al., 2012; Davis et al., 2009) and grammar (Ellis and Schmidt, 1997; Merkx et al., 2011; Morgan-Short et al., 2012a, 2012b). Importantly, performance at artificial language learning has been found to correlate positively with natural second language learning (Ettlinger et al., 2016), and training on an artificial language can result in native-like brain activity patterns (Morgan-Short et al., 2012a, 2012b). Thus, results from artificial languages show a likelihood of generalizability to natural languages.

Note that although researchers have used artificial language paradigms as models of first language acquisition (e.g., Karuza et al., 2013), in the present study we interpret the learning and generalization of the artificial language as a model of second language learning (e.g., Morgan-Short et al., 2012a, 2012b), since in this study learning occurs in adulthood (when participants have already learned at least their first language), and moreover, as in a second language, the artificial language involved learning inflections for familiar items (e.g., apple; see Methods).

We are aware of three artificial language studies investigating the influence of affix type frequency on the learning or generalization of affixal inflection. In two studies, Ellis and Schmidt (1997, 1998) found that higher affix type frequency facilitates the acquisition of trained inflected forms in an artificial language. Similarly, Bybee and Newman (1995) observed that higher affix type frequency improved the generalization of affixes to untrained words.

Additionally, in a recent artificial language study we examined the effects of both affix phonological predictability and affix type frequency on the learning and generalization of affixal inflection (Nevat et al., under review). In this purely behavioral study, we used an artificial language paradigm similar (but not identical) to the one examined in the present study. Three groups of adult participants were trained on plural inflectional suffixes in the artificial language, with an orthogonal manipulation of suffix type frequency and phonological predictability across groups. The results indicated that participants inflected trained words with high-frequency suffixes more accurately than those with medium- and low-frequency suffixes (with the worst performance on those with medium-frequency suffixes). Moreover, for untrained words participants relied on the predictability of rime cues when selecting the affix, a reliance which increased with exposure to the language. These findings reveal the importance of both suffix type frequency and suffix phonological predictability in the learning and generalization of affixal morphological inflection in an artificial language learned as an adult.

1.2. Relevant theoretical and empirical neurocognitive research

Although behavioral studies are beginning to elucidate the influence of affix type frequency and affix predictability on affixal inflection, as mentioned above we are aware of no prior research on the neural bases of the effects of these factors on affixal inflection, nor more generally on the functional neuroanatomy of the learning and generalization of affixal inflection. Nevertheless, prior theoretical and empirical neurocognitive research on other aspects of language provides a foundation on which to examine these issues.

1.2.1. A neurocognitive theoretical account: the declarative/procedural model

A number of neurocognitive models have been proposed to explain the processes involved in learning and processing a second language, and how these may differ, overlap, or interact with those underlying first language (e.g., Abutalebi, 2008; Clahsen and Felser, 2006; Hernandez et al., 2005; Paradis, 1994; Ullman, 2015). The model that appears to make the most specific neuroanatomical predictions for grammar learning in a second language, and which provides our primary predictions, is the Declarative/Procedural (DP) model (Ullman, 2001a, 2001b, 2004, 2005, 2015, 2016). We therefore focus on this model here. Note that this does not imply that the other models