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Voxel-based lesion-parameter mapping: Identifying the neural correlates of a computational model of word production

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ABSTRACT

The *dual-route interactive two-step model* explains the variation in the error patterns of aphasic speakers in picture naming, and word and nonword repetition tasks. The model has three parameters that can vary across individuals: the efficiency of the connections between semantic and lexical representations (*s*-weight), between lexical and phonological representations (*p*-weight), and between representations of auditory input and phonological representations (*nl*-weight). We determined these parameter values in 103 participants with chronic aphasia from left hemisphere stroke whose lesion locations had been determined. Then, using *voxel-based lesion-parameter mapping*, we mapped the parameters onto the brain, thus determining the neural correlates of the model's mechanisms. The maps and the behavioral findings supported the model's central claim that word repetition is affected by both the *p* and *nl* parameters. We propose that these two parameters constitute the model's analogue of the "dorsal stream" component of neurocognitive models of language processing.

1. Introduction

Most computational models of cognition aim to simulate behavioral data. For example in the domain of language production, the topic of this article, models simulate speaker choices (e.g. Chang, Dell, & Bock, 2006), the temporal dynamics of those choices (e.g. Levelt, Roelofs, & Meyer, 1999), and the characteristics of speech errors, including normal slips as well as production errors made by speakers with brain damage (e.g. Dell, Schwartz, Martin, Saffran, & Gagnon, 1997). To explain these data, the models postulate representations and processes, and parameters regarding how these vary across individuals and circumstances.

More recently, cognitive models have been used to guide cognitive neuroscience. The models identify cognitive functions whose brain correlates can be sought. Language production models, in particular, have been used to interpret functional imaging data obtained from a variety of methods (e.g. Costa, Strijkers, Martin, & Thierry, 2009; Graves, Grabowski, Mehta, & Gordon, 2007; Indefrey & Levelt, 2004; Price, 2000) and analyses of lesion locations in speakers with aphasia (e.g. DeLeon et al., 2007; Schwartz et al., 2009). In this article, we identify the neural correlates of a particular model of lexical access in production, the *dual-route interactive two-step model* (e.g. Dell, Martin, & Schwartz, 2007; Hanley, Dell, Kay, & Baron, 2004; Nozari, Kittredge, Dell, & Schwartz, 2010; Schwartz, Dell, Martin, Gahl, & Sobel, 2006). This and related models have been applied to several aspects of lexical processing in aphasic and unimpaired speakers.

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Here, the focus is on the relationship between word production from meaning, for example, in the picture naming task, and production in the auditory repetition task, in which speakers repeat heard words or nonwords. Relating the model's characteristics to the brain can, at the very least, provide a test of the model by determining whether its distinctions map onto the brain in an interpretable way. Perhaps more importantly, this test can also constrain other recent models that make specific claims about brain pathways that are relevant for production (e.g., Hickok, 2012; Hickok & Poeppel, 2004; Ueno, Saito, Rogers, & Lambon Ralph, 2011). That is, we hope to take a first step in linking a cognitive model of production that simulates speech errors made by normal and impaired speakers to neurocognitive models of language that have been developed from different data sources.

Our methods are based on *voxel-based lesion symptom mapping* (VLSM, Bates et al., 2003). VLSM is one of a family of fMRI-inspired techniques aimed at identifying voxels or anatomically defined regions in which the presence or extent of tissue dysfunction predicts a symptom at a statistically reliable level (e.g., Hillis et al., 2006; Kimberg, Coslett, & Schwartz, 2007; Rorden, Karnath, & Bonilha, 2007; Rudrauf et al., 2008). The typical VLSM study involves a large sample of individuals with chronic focal lesions who have been assessed on the symptom of interest and have undergone a structural brain scan to locate the lesion. The lesions are traced and registered to a common template, enabling a determination at each voxel of who had a lesion in that voxel and who did not. In each voxel, a statistic is computed measuring the association between lesion status and the presence or severity of the symptom. Using a threshold that corrects for the many thousands of tests performed, voxels are identified that exceed the threshold and thereby qualify as being related to the symptom in question.

In this article, we present results of a specific kind of VLSM, called voxel-based lesion *parameter* mapping (VLPM). VLPM is just like VLSM, except that voxel lesion status predicts the properties of the model's characterization of patients, rather than patient symptoms directly. The dual-route interactive two-step model has three parameters on which aphasic individuals can differ, *s* (semantic) weight, *p* (phonological) weight, and *nl* (nonlexical) weight. Each patient is assigned a value for these parameters based on a set of procedures for fitting the model to the patient's error patterns in a picture naming test and an auditory repetition test. For this article, we performed this model evaluation for 103 individuals with post-stroke aphasia and used VLPM to create brain maps that identify which voxels predict the variation in the parameters.

1.1. The dual-route interactive two-step model

The model explains the errors that aphasic speakers make in picture naming (hereafter, naming) and auditory repetition. The details of its architecture, processing mechanisms, and parameter fitting procedures are described elsewhere (e.g. Dell et al., 2007; Schwartz et al., 2006), but we provide a short summary of these and some background. The earliest version of the model explained speech error patterns from normal speakers in spontaneous sentence production (Dell, 1986). Its key assumptions were that representations of the utterance to be spoken are constructed at semantic, syntactic, morphological, and phonological levels, and the items that participate in these representations are retrieved through spreading activation in a network of linguistic units. When the model was first applied to aphasia, a version that simulated single-word utterances was created (Martin, Dell, Saffran, & Schwartz, 1994). This model was initially set up so that it mimicked normal performance. Parameters values were chosen to make the model's error patterns in retrieving words match that of normal controls in a picture naming task (Dell et al., 1997). Then the model was "lesioned" in an attempt to simulate aphasia. In this respect, the model is, first and foremost, a model of production, and only secondarily a model of impaired production. Over the past 15 years, however, much of the work that has developed and tested the model has used data from aphasic speakers (e.g. Hanley & Nickels, 2009; Rapp & Goldrick, 2000; but see Budd, Hanley, & Nozari, 2012, for an application of the model to normally developing children). Moreover, although these applications have concerned single-word production, it is worth noting that the model's lexical selection mechanism is constrained by the utterance's syntactic-sequential structure. This mechanism has been tested with sentence production data (Dell, Oppenheim, & Kittredge, 2008).

In its present form, the model consists of an interconnected network of semantic, lexical, and output phonological units, and a further set of connections between auditorily presented verbal input and the output phonological units, as shown in Fig. 1. All connections are bidirectional, thus making the model's flow of activation interactive. In naming, lexical access starts with a jolt of activation to the target word's semantic features. This activation flows through the network and, after a fixed period

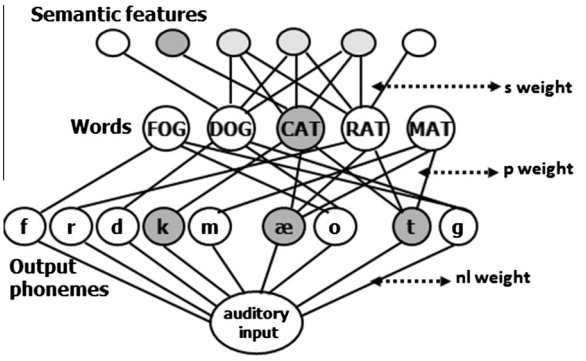

Fig. 1. The dual-route interactive two step model and its three parameters. For the naming task, the semantic features are activated and selection occurs first at the word level, and then at the output phonemes. For nonword repetition, the auditory input node is activated and selection occurs at the output phonemes. For word repetition by the lexical route, the target word node is activated and selection occurs at the output phonemes. For dual-route word repetition, both the target word node and the auditory input node are activated, and selection occurs at the output phonemes.