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Unification of behavioural, computational and neural accounts of word production errors in post-stroke aphasia

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ABSTRACT

Neuropsychological assessment, brain imaging and computational modelling have augmented our understanding of the multifaceted functional deficits in people with language disorders after stroke. Despite the volume of research using each technique, no studies have attempted to assimilate all three approaches in order to generate a unified behavioural-computational-neural model of post-stroke aphasia.

The present study included data from 53 participants with chronic post-stroke aphasia and merged: aphasiological profiles based on a detailed neuropsychological assessment battery which was analysed with principal component and correlational analyses; measures of the impairment taken from Dell's computational model of word production; and the neural correlates of both behavioural and computational accounts analysed by voxel-based correlational methodology.

As a result, all three strands coincide with the separation of semantic and phonological stages of aphasic naming, revealing the prominence of these dimensions for the explanation of aphasic performance. Over and above three previously described principal components (phonological ability, semantic ability, executive-demand), we observed auditory working memory as a novel factor. While the phonological Dell parameter was uniquely related to phonological errors/factor, the semantic parameter was less clear-cut, being related to both semantic errors and omissions, and loading heavily with semantic ability and auditory working memory factors. The close relationship between the semantic Dell parameter and omission errors recurred in their high lesion-correlate overlap in the anterior middle temporal gyrus. In addition, the simultaneous overlap of the lesion correlate of omission errors with more dorsal temporal regions, associated with the phonological parameter, highlights the multiple drivers that underpin this error type. The novel auditory working memory factor was located along left superior/middle temporal gyrus and ventral inferior parietal lobe.

The present study fused computational, behavioural and neural data to gain comprehensive insights into the nature of the multifaceted presentations in aphasia. Our unified account contributes enhanced knowledge on dimensions explaining chronic post-stroke aphasia, the variety of factors affecting inter-individual variability, the neural basis of performance, and potential clinical implications.

1. Introduction

Behavioural assessment and computational modelling are important tools to understand the diverse patterns of impaired performance in people with aphasia (PWA) (Basilakos et al., 2014; Rogalsky et al., 2015; Ueno et al., 2011; Walker and Hickok, 2016; for a review see Cahana-Amitay and Albert, 2015). More recently, each approach has been linked with brain lesion data to investigate the neural basis of aphasia. Thus, the computational parameters of the Dell model (Dell et al., 2013; Schwartz et al., 2012) or behavioural assessment results (Butler et al., 2014; Halai et al., 2017; Mirman et al., 2015a,b) have been associated with distinct regions in the brain. However, to date there has been no attempt to unify behavioural, computational and neuroimaging data in order to gain a more comprehensive, multi-level understanding of aphasia. Therefore, the purpose of the present study was to converge: (i) the principal components of aphasic performance based on behavioural data; (ii) measures of the impairment taken from a computational model of aphasic naming; and, (iii) the neural correlates of both behavioural and computational factors. We present principal component and correlational analyses of data from a large

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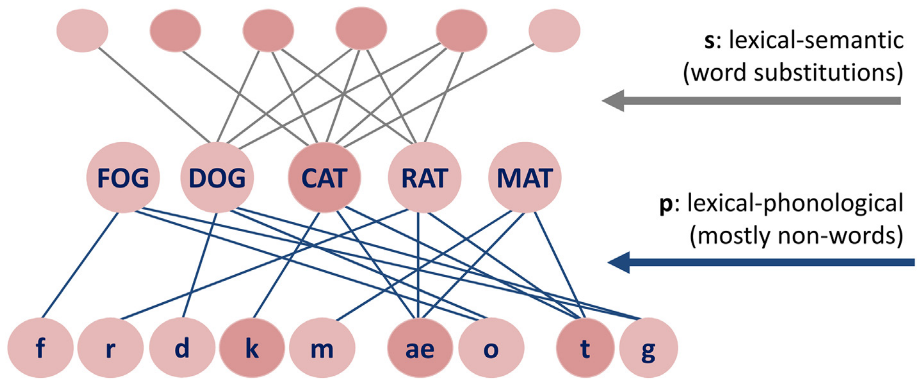

Fig. 1. Impairment types in the Dell model (Foygel and Dell, 2000). The model includes a semantic feature layer, an intermediate lexical layer with word entries, and a phonological layer. Nodes of neighbouring layers are bi-directionally connected. The model features a two-stage access of lexical and then phonological entries, which occurs via spreading activation along the connections in the network.

neuropsychological assessment battery and from computer simulations in the Dell interactive two-step model of word production (Abel et al., 2009; Dell et al., 1997, 2013; Foygel and Dell, 2000; Schwartz et al., 2006), with subsequent mapping of the model parameters and behavioural PCA components onto the brain using voxel-based correlational methodology (VBCM: Basilakos et al., 2014; Butler et al., 2014; Halai et al., 2017; Tyler et al., 2005). By merging these three levels of description from behavioural, computational and neuroimaging disciplines, we offer converging evidence on the theoretical and neural bases of the variety of behavioural presentations in aphasia.

1.1. Interactive two-step model

In accordance with other models of word production (see overview in Rapp and Goldrick, 2006), Dell's interactive two-step model of word production (Foygel and Dell, 2000) assumed lexical functions to be split into semantic and phonological processes. The cognitive model aimed to explain intact and impaired performance in confrontation naming. It contained three layers of interconnected nodes as shown in Fig. 1, namely semantic feature nodes depicted at the top, lexical nodes in the middle, and phonological nodes at the bottom. Naming occurred in two retrieval steps: first, lexical retrieval through activation spreading from semantic feature nodes to lexical nodes; and second, phonological retrieval through activation spreading from lexical to phonological nodes. The flow of activation between layers was interactive, spreading along bidirectional connections between neighbouring layers, and it was modulated by the weights of lexical-semantic connections (*s*) and lexical-phonological connections (*p*), respectively. The model explained naming errors in aphasic speakers by attributing the impairment to reduced semantic and/or phonological weights, with the former being broadly associated with word errors and the latter with mainly non-words. Thus, smaller parameter weights indicated greater impairment.

A recent paper by Dell et al. (2013), suggested that the model parameters include more processes than previously assumed, drawing their conclusion from regression analyses of behavioural data and voxel-based lesion-parameter mapping (VLPM). As in voxel-lesion symptom mapping (VLSM: Bates et al., 2003), VLPM attempts to relate the variation in model parameters for each patient to the status of voxels across the brain (intact or lesioned). While in earlier versions of the Dell model the parameters were thought to be restricted to connection weights within the lexicon only, current understanding assumes that the *s* parameter represents semantic representations and semantic control processes over and above the lexical-semantic weight. The *p* parameter includes phonological representations and aspects of articulation over and above the lexical-phonological weight. Walker and Hickok (2016) recently provided a new fitting algorithm and website (http://www.cogsci.uci.edu/~alns/webfit) for the SP-model by Foygel and Dell (2000). It constrains parameter values to be below a presumably normal level, and thereby provides an improved fit.

1.2. Principal component analysis

Recent studies have demonstrated the separation of semantic, phonological and other cognitive processes in aphasic performance by use of varimax rotated principal component analysis (PCA) (Butler et al., 2014; Halai et al., 2017; Lambon Ralph et al., 2002; Mirman et al., 2015a,b). PCA can be used as a useful exploratory tool as it can extract the components that underlie a set of correlated variables (e.g., the latent structure underlying a large neuropsychological battery). To do so, variance in the variables is first redistributed across an equal number of components as there are variables. In a second step, a predefined criterion is used to extract only as many components as necessary to explain a 'sufficient' amount of variance. Components can then be rotated, which allows clearer cognitive interpretation of the components while maintaining their orthogonality. While it is possible to allow oblique rotation of components, maintaining orthogonality in this investigation is useful for at least two reasons. First, a number of computational models have been developed for the language domain, with independent processes/layers representing fundamentally independent processes such as phonology, semantics and speech output (e.g., Dell et al., 2013; Ueno et al., 2011). In addition, co-linearity in neuroimaging analyses is problematic when mapping behaviours to the brain, as the shared variance is partitioned out and the model estimates parameters based on the remaining variance, which can be noisy. As neuropsychological data are typically highly co-linear, a method to orthogonalise the data (such as PCA) has been shown to be useful in producing more interpretable neuroimaging results (see Butler et al., 2014).

Butler et al. (2014) and Halai et al. (2017) investigated the components that contribute to performance of people with aphasia (PWA) on neuropsychological tasks that involve cognitive and language functions. Along with a phonological and a semantic factor, the two studies have shown executive processing to contribute to aphasic performance. In the follow up study, Halai et al. (2017) found that speech fluency also emerged as a statistically independent factor in addition to phonology, semantics and executive function. Using a similar methodology, Mirman et al. (2015a,b) investigated semantic and phonological error rates in the context of a wide language test battery and found four factors that were assumed to reflect a division of the language system into semantic versus phonological processes, and recognition versus production. Of these four factors identified, semantic recognition and speech production can be related to semantic and phonological factors mentioned above (Butler et al., 2014; Halai et al., 2017), respectively. Interestingly, while phonological error rate aligned with speech production, semantic errors did not load strongly on any of the first three factors but formed an independent fourth factor with only small loadings for the other assessments, indicating that they are relatively independent of the other factors.

One can pose the question as to how the *s* and *p* parameters from the Dell model relate to the PCA factors found to be crucial in describing