

Emily Upton & Thomas M. H. Hope

Moving beyond the dual stream account of language

The dual stream account of language distinguishes (i) a ventral stream, involving the anterior and posterior temporal lobe and the inferior parietal lobe, and concerned primarily with sound-to-meaning mapping; from (ii) a dorsal stream, involving the parietal lobe, the posterior superior temporal lobe and the posterior frontal lobe, and with an emphasis on sound-to-articulation mapping (Hickok and Poeppel, 2004) (see Figure 1a). Though very well-supported, this distinction also leaves a lot of detail unresolved, including how these streams interact with other ‘off-stream’ cognitive functions, and how distinct they really are. In this issue of *Brain*, Hula and colleagues address these questions by interrogating the relationships between the errors that a sample of stroke survivors make when naming common objects, and the white matter disruption caused by their strokes (Hula et al., 2020).

One enduring challenge for studies like this, is that the behavioural performance we can measure is likely the result of a complex interaction between multiple cognitive components. To name the object displayed in a picture for example, we must (at least) understand and remember the task instructions, look at the picture and recognise the object, all before we can retrieve and articulate its name. Impaired task performance might emerge from disruption to any of these stages, either singly or in combination, thus complicating the inference from behavioural impairment to cognitive impairment. One response to this problem has been to extract latent variables from scores on wide-ranging batteries of tasks: the intuition being that these variables might better correspond to those putatively separable (e.g. semantic vs. phonological) underlying cognitive processes (e.g. (Butler *et al.*, 2014)). But this is a data-hungry method that ideally requires large sample sizes, and there is no guarantee that it will yield interpretable results. Hula and colleagues take the more unusual but certainly less data-hungry approach of distinguishing the separable cognitive processes presumed to underlie the error types observed in naming, in terms of the key parameters of a generative model that can produce those same errors.

The Semantic-Phonological interactive two-step (SP) model is a localist neural network, consisting of semantic, lexical and phonological layers of units (Dell *et al.*, 1997) (see Figure 1b). SP models construe naming as a two-step process, starting with a jolt of activity to the semantic units associated with a target word, which flows through the model for a set number of iterations until the winning (most activated) lexical or word unit is selected. A further jolt of activity to this unit begins the second step, spreading through the model for another fixed number of iterations before the winning phonological units are selected. Noise in the system interacts with the spreading activation, causing occasional semantic or phonological errors, and particular profiles of errors can also be encouraged by changing (weakening) the weights on connections between either the semantic and lexical layers (*s*), or the lexical and phonological layers (*p*). These parameters can therefore be tuned to match the types and frequencies of naming errors generated by the model, to the empirical error distributions recorded when individual patients engage in naming. Hula and colleagues fit SP models to each of their patients’ empirical error profiles, deriving a simple, two-parameter representation corresponding to a rich, generative model of each patient’s naming performance.

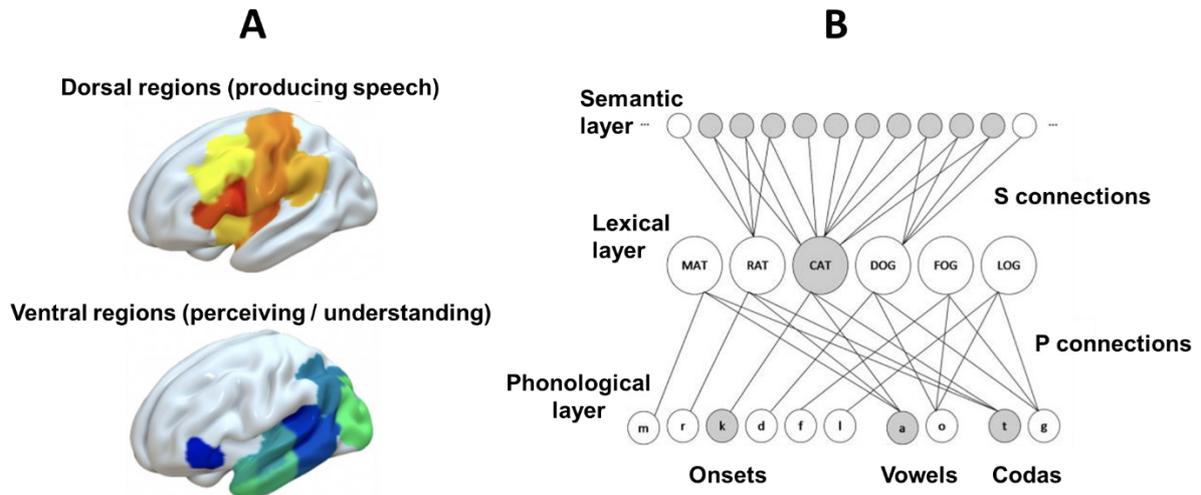


Figure 1: (A) Left hemisphere brain regions implicated in the dorsal (top) and ventral (bottom) streams, respectively. **(B)** A schematic representation of an SP two-step interactive model, with semantic, lexical and phonological units highlighted for a target word ‘CAT’. Brain images courtesy of Julius Fridriksson (Aphasia Lab).

The authors relate these fitted parameters to white matter connectivity derived from diffusion imaging data, via a relatively unusual ‘bottom-up’ form of connectometry analysis focused on defining the local orientations and integrity of fibre bundles within white matter tracts. This is in contrast to (and may be more sensitive than) more common ‘top-down’ analyses, focused on finding tracks to connect pre-defined cortical parcels (Yeh *et al.*, 2016). Identifying potentially disrupted tracts by comparison to neurologically normal controls, the authors then used multiple regression to measure associations between disrupted connectivity and both *s* and *p*, while controlling for lesion volume. Their results illustrate both the strengths and the weaknesses of dual stream accounts of language. On the one hand, the tracts identified with *s* and *p* were arranged in a ventral-dorsal configuration (see Figure 4 in Hula *et al.*). But both parameters were significantly associated with connectivity in the middle longitudinal fasciculus, and there were also significant associations between *s* and *p* with tracts beyond the plausible purview of either of the streams.

The dual stream account can accommodate the blurring of the dorsal-ventral distinction implied by these results: given increasing evidence that many (perhaps most) neurobiological structures support multiple functions (Anderson, 2010), a completely discrete division of labour between the streams was already implausible. And that result is also consistent with another recent report, relating rates of semantic paraphasias in naming to disruption in both streams (Fridriksson *et al.*, 2018). But it is also possible that both results reflect the reorganisation of the language system after stroke, rather than its neurologically normal organisation – and in some ways this would be the more compelling result, because we know so little about how that reorganisation occurs. As Hula and colleagues note, this latter interpretation is consistent with a prior observation of ventral (semantic) stream recruitment in a (primarily phonological) word repetition task, after lesions to a neuroanatomically constrained model of word production called Lichteim 2 (Ueno *et al.*, 2011). Perhaps the most direct way to test this interpretation would be to study analogous damage-deficit associations in stroke survivors at a more acute stage. If the tract-sharing that Hula and colleagues observe here is a function of neuroplasticity in recovery, it should be less evident or absent sooner after stroke.

Crucially though, s and p are parameters in an abstract neurocognitive model which, while certainly useful and also at least plausibly consistent with the dual stream account of language, is only indirectly related to the cognitive architecture of naming. The temptation to interpret these connectivity parameters literally, as characteristics of the ventral and dorsal stream connectivity respectively, is as the authors note unfortunately unsustainable. Indeed, this was one conclusion of the most comprehensive, prior analysis of these parameters' neurobiological correlates (Dell *et al.*, 2013), which offered expanded interpretations of both: adding somatosensory influences on phonological errors to the scope of p , and adding semantic control and even semantic representation (over-and-above semantic-lexical connections) to the scope of s . Hula and colleagues' 'off-stream' associations between both parameters and tracts implicated in hippocampal and default mode networks further extend this trend, emphasising the wider cognitive context in which the dual streams likely operate to produce behaviour. These extensions are natural next steps in our models of basic language skills. In an interconnected brain, the dual streams were never going to tell the whole story on their own (Hickok and Poeppel, 2015).

In allowing for extended interpretations of s and p , we are effectively using the SP model as another form of dimensionality reduction – like principal component analysis (and subject to analogous interpretability challenges), but with different assumptions and constraints. This is both necessary and productive in Hula and colleagues' study, but it does also whet the appetite for generative models of basic language skills that might support more literal interpretations of derived parameters.

Glimpses of how such a *computational cognitive neurology* of stroke might work, are increasingly abundant, but no single approach yet combines all the necessary features. SP models capture behavioural performance with individual-level specificity, but are only ambiguously related to neurobiology. Connectome network models, inverted from individual patients' structural and functional brain imaging data, have the opposite profile of strengths and weaknesses: they employ both explicit and individually specific neurobiology, but cannot yet account for behavioural performance in desirable levels of detail (Falcon *et al.*, 2016). And while neuroanatomically constrained models, like Lichteim 2, are explicit at both the behavioural and the neurobiological levels, they currently lack individual-level specificity at either level.

The coherent combination of these different approaches' benefits – of integrated, individual-level specificity at both the brain and the behavioural levels – could dramatically accelerate our understanding of the neurobiology of basic cognitive skills in health and disease. Hula and colleagues' study encourages us to look beyond the simple constructs that have dominated our understanding of language so far, and also offers a glimpse of a more detailed and productive, model-based future for analyses relating brain damage to profiles of consequent cognitive impairment.

References

Anderson ML. Neural reuse: a fundamental organizational principle of the brain. *The Behavioral and brain sciences* 2010; 33(4): 245-66; discussion 66-313.

Butler RA, Lambon Ralph MA, Woollams AM. Capturing multidimensionality in stroke aphasia: mapping principal behavioural components to neural structures. *Brain : a journal of neurology* 2014; 137(12): 3248-66.

Dell GS, Schwartz MF, Martin N, Saffran EM, Gagnon DA. Lexical access in aphasic and nonaphasic speakers. *Psychological review* 1997; 104(4): 801.

Dell GS, Schwartz MF, Nozari N, Faseyitan O, Branch Coslett H. Voxel-based lesion-parameter mapping: Identifying the neural correlates of a computational model of word production. *Cognition* 2013; 128(3): 380-96.

Falcon MI, Jirsa V, Solodkin A. A new neuroinformatics approach to personalized medicine in neurology: The Virtual Brain. *Curr Opin Neurol* 2016; 29(4): 429-36.

Fridriksson J, den Ouden D-B, Hillis AE, Hickok G, Rorden C, Basilakos A, *et al.* Anatomy of aphasia revisited. *Brain : a journal of neurology* 2018.

Hickok G, Poeppel D. Dorsal and ventral streams: a framework for understanding aspects of the functional anatomy of language. *Cognition* 2004; 92(1-2): 67-99.

Hickok G, Poeppel D. Neural basis of speech perception. *Handbook of Clinical Neurology*; 2015. p. 149-60.

Hula W, Panesar S, Gravier M, Fang-Cheng Y, Dresang H, Dickey M, Fernandez-Miranda J. Structural white matter connectometry of word production in aphasia: an observational study. *Brain* 2020.

Ueno T, Saito S, Rogers TT, Lambon Ralph MA. Lichtheim 2: synthesizing aphasia and the neural basis of language in a neurocomputational model of the dual dorsal-ventral language pathways. *Neuron* 2011; 72(2): 385-96.

Yeh F-C, Badre D, Verstynen T. Connectometry: A statistical approach harnessing the analytical potential of the local connectome. *NeuroImage* 2016; 125: 162-71.