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The evolution of cognitive models: From neuropsychology to neuroimaging and back

Cathy J. Price *

Wellcome Centre for Human Neuroimaging, Institute of Neurology, University College London, London, UK

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ABSTRACT

This paper provides a historical and future perspective on how neuropsychology and neuroimaging can be used to develop cognitive models of human brain functions. Section 1 focuses on the emergence of cognitive modelling from neuropsychology, why lesion location was considered to be unimportant and the challenges faced when mapping symptoms to impaired cognitive processes. Section 2 describes how established cognitive models based on behavioural data alone cannot explain the complex patterns of distributed brain activity that are observed in functional neuroimaging studies. This has led to proposals for new cognitive processes, new cognitive strategies and new functional ontologies for cognition. Section 3 considers how the integration of data from lesion, behavioural and functional neuroimaging studies of large cohorts of brain damaged patients can be used to determine whether inter-patient variability in behaviour is due to differences in the premorbid function of each brain region, lesion site or cognitive strategy. This combination of neuroimaging and neuropsychology is providing a deeper understanding of how cognitive functions can be lost and re-learnt after brain damage – an understanding that will transform our ability to generate and validate cognitive models that are both physiologically plausible and clinically useful.

1. Introduction

The motivation for this paper was to describe a journey of thoughts and theories about cognitive models of human brain function that were initiated by conducting neuropsychological and neuroimaging studies with Glyn Humphreys. Previous discussions of how neuroimaging has contributed to cognitive models were the focus of a special issue of Cortex more than 10 years ago. The lead article (Coltheart, 2006a) argued in line with others previously (e.g., Colby, 1978; Harley, 2004; Marr & Poggio, 1977; Uttal, 2001) that knowing about neural implementation of cognitive processing had not to date (2006) informed or changed our cognitive models. The debate centred on whether there was any evidence that neuroimaging had provided new insights that adjudicated between two alternative cognitive models. Although several examples were offered (Henson et al., 2006; Jack, Sylvester, & Corbetta, 2006; Jonides, Nee, & Berman, 2006; Seron & Fias, 2006; Vallar,

* Wellcome Centre for Human Neuroimaging, Institute of Neurology, University College London, 12 Queen Square, WC1N 3AR, London, UK.
E-mail address: c.j.price@ucl.ac.uk.
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2006), Coltheart (2006b) and others (Page, 2006; Schutter, de Haan, & van Honk, 2006) argued that none of them had contributed any more information than could have been gained from behavioural studies alone. More recently, in a special issue of Perspectives in Psychological Science (Mather, Cacioppo, & Kanwisher, 2013a), Coltheart (2013) further emphasized that the contribution of neuroimaging data to a cognitive theory should not be based on the consistency of neuroimaging data with predictions from cognitive theory. It should be based on falsifying the predictions of a particular theory.

In the current paper, I take a different perspective and focus on how neuroimaging has changed the way we think about the functional computations (types of cognitive processing) that underlie behaviour. I start by introducing the rationale, fascination and limitations of neuropsychology. The bottom line is that we do not know how cognitive functions are implemented in the brain. We can only speculate and approximate on what the underlying computations are and how they are instantiated. I then discuss what neuroimaging has told us about the general principals of neuronal implementation and how the nature of the neuronal implementation constrains the nature of the computations and algorithms that are being performed. Therefore, this paper is not about the functions of different brain regions (i.e., the functional anatomy). It illustrates how learning about the anatomy can shed new light on what the computations underlying cognition might be.

The discussion of neuroimaging findings also highlights the fact that we don't know what is being coded and we do not yet have a formal terminology to assign functional labels to brain regions. For example, most cognitive models of reading and spelling refer to “orthographic processing”. This simply means processing related to written text but it doesn't specify the nature of the processing or the degree to which this processing is shared by non-orthographic visual stimuli. I consider why current psychological nomenclature is insufficient to describe the function of brain areas and how neuroimaging is motivating new terminology, new brain functions and new cognitive models.

In the final section, I highlight the benefits of integrating data from neuroimaging and neuropsychology. In brief, I show how neuroimaging can be used to distinguish between 3 different types of inter-patient variability: differences in (i) lesion site, (ii) the brain structures that compute a given function, and (iii) the cognitive strategy used for a given task even when the structure–function mapping is consistent at the individual process level. This helps to provide a deeper understanding of computational functions, processing pathways, co-occurring impairments and how the same functional impairment (and lesion site) can lead to different symptoms.

2. Section 1: Using neuropsychology to inform cognitive models

Neuropsychology involves the study of behaviour in patients with neurological disorders. By indicating how brain damage impacts on behaviour, neuropsychological studies can test and infer models of the computations that underlie specific cognitive functions (e.g., language, memory, perception) in the neurologically normal brain. The most famous examples of neurological studies date back to the 19th Century when Paul Broca reported that patients with left posterior inferior frontal damage had more difficulty with speech production than speech comprehension; and conversely, Karl Wernicke noted that patients with damage to the left posterior superior temporal cortex had more difficulty with speech comprehension than production. This “double dissociation” in cognitive function (across different patients) indicated that speech production and comprehension are functionally independent of one another.

Bringing Broca's and Wernicke's findings together, Ludwig Lichtheim developed a simple processing model of language that linked auditory representations of speech (in Wernicke's area) to motor representations of speech (in Broca's area) via anatomical connections through the arcuate fasciculus. Jules Dejerine added to the model (1891) by including visual images of speech in the left angular gyrus/supramarginal gyrus where damage could result in a selective reading difficulty that dissociated from relatively preserved spoken language and writing abilities. Dejerine therefore coined the term “pure alexia” to describe a very specific deficit confined to the impaired processing of orthographic code rather than a more general perceptual disturbance (see Bub et al., 1993 for a full description).

Fig. 1 illustrates the 19th Century neurological model of language and reading. Other 19th Century neurological investigations reported double dissociations in other cognitive functions leading to a deeper understanding of hand movement control and its breakdown in different types of apraxia (Liepmann, 1900) and object recognition and its break down in different types of agnosia (Lissauer, 1890).

After the early 19th Century attempts to localise mental functions to brain structures, most neuropsychologists in the

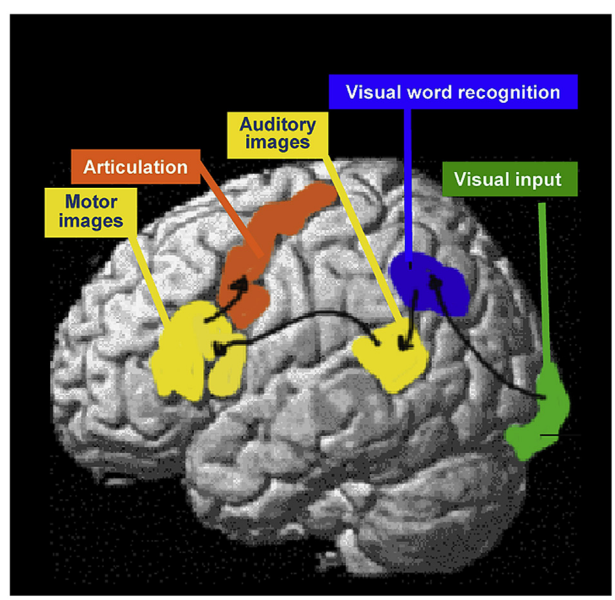

Fig. 1 – The Neurological model of Language. An illustration of the anatomical and functional processing pathways that were hypothesized on the basis of post mortem studies conducted in the late 19th Century.

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