Neuropsychologia 98 (2017) 68–84

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

Learning and retrieving holistic and componential visual-verbal associations in reading and object naming

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ARTICLE INFO

Keywords:
FMRI
Reading
Learning
Orthography
Consolidation

ABSTRACT

Understanding the neural processes that underlie learning to read can provide a scientific foundation for literacy education but studying these processes in real-world contexts remains challenging. We present behavioural data from adult participants learning to read artificial words and name artificial objects over two days. Learning profiles and generalisation confirmed that componential learning of visual-verbal associations distinguishes reading from object naming. Functional MRI data collected on the second day allowed us to identify the neural systems that support componential reading as distinct from systems supporting holistic visual-verbal associations in object naming. Results showed increased activation in posterior ventral occipitotemporal (vOT), parietal, and frontal cortices when reading an artificial orthography compared to naming artificial objects, and the reverse profile in anterior vOT regions. However, activation differences between trained and untrained words were absent, suggesting a lack of cortical representations for whole words. Despite this, hippocampal responses provided some evidence for overnight consolidation of both words and objects learned on day 1. The comparison between neural activity for artificial words and objects showed extensive overlap with systems differentially engaged for real object naming and English word/pseudoword reading in the same participants. These findings therefore provide evidence that artificial learning paradigms offer an alternative method for studying the neural systems supporting language and literacy. Implications for literacy acquisition are discussed.

1. Background

In recent years the education literature has settled upon phonics as the only evidence-based method of teaching reading (Torgerson et al., 2006; Wyse and Goswami, 2008). Indeed, in the UK, the Rose Review (Rose, 2006) recommended that synthetic phonics, which involves explicit instruction in letter-sound decoding and blending, should underlie early reading instruction. This provides children with the primary skill of being able to translate *print to sound*. Whole-word methods of reading instruction instead argue for the primacy of meaning in reading, with knowledge of letter-to-sound mappings being acquired through exposure to meaningful text. In this case the primary skill of reading should not be translating *print to sound*, but instead *print to meaning*. Correspondingly the focus of early learning in whole-word reading schemes is to recognise whole ‘sight words’, rather than decoding the letter-sound correspondences within each word. Thus, many are sceptical of whether, in line with the Rose Review, phonics should be taught “first and fast”. While experimental data has an important role to play in this activity, Wyse and Goswami (2008) note that very few naturalistic studies comparing different methods of reading instruction meet rigorous experimental standards. In this paper we consider whether laboratory studies of holistic and componential visual-to-verbal learning may offer a way to address educational questions in a controlled manner.

The distinction between recognising whole-words and decoding letter-by-letter in the educational literature is mirrored to a large extent by findings from cognitive research on reading. Cognitive models of reading, such as the Dual Route Cascaded (DRC) and triangle model, reflect the distinction between holistic and componential processing by suggesting that the meaning of a written word can be accessed in more than one manner (Coltheart et al., 2001; Plaut et al., 1996). For example, in the DRC model, words can be read componentially by decoding letter-by-letter (sub-lexical route), or can be mapped onto their pronunciations and meanings directly by recognising the whole word form (lexical route). It is the componential relationship between visual and phonological forms in alphabetic languages that means we

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http://dx.doi.org/10.1016/j.neuropsychologia.2016.09.025
Received 19 February 2016; Received in revised form 5 August 2016; Accepted 28 September 2016
Available online 06 October 2016

can read pseudowords, e.g. 'spape', using our knowledge of letter-sound mappings. In contrast, to read an irregular word (e.g. 'pint') we must have whole-word knowledge to know that it does not sound similar to words that share the same orthographic components ('mint', 'hint', etc.). In the triangle model (Plaut et al., 1996) the mappings between written (orthographic) and spoken (phonological) forms are componential; this model does not contain whole-word, or lexical, representations of this information. However, in this model, the relationship between a familiar word's written form and its meaning is more holistic and item-specific, since the form-to-meaning mapping cannot be broken down into sub-components, at least for monomorphemic words (i.e. most monosyllabic words). Furthermore, this item-specific knowledge is proposed to be important for irregular word reading, helping them to be pronounced differently from similarly spelled regular words. Thus, both the DRC and the triangle model propose that reading involves both componential and whole-word knowledge, with the former being more important for pseudowords or less familiar words, and the latter more important for words, in particular those with irregular spellings.

Although both componential (sub-lexical) and holistic (lexical) processes are involved in skilled reading it is not clear how the relative importance of these skills changes as we learn to read. The goal of the present study was to advance our understanding of the initial stages of reading acquisition by exploring the neural basis of componential and holistic processing. To do so we compared learning to read an artificial alphabetic orthography with systematic symbol-to-sound mappings with learning names for novel objects with arbitrarily associated names.

1.1. Neural bases of holistic and componential processes in reading

The ventral occipito-temporal (vOT) cortex, including posterior and anterior fusiform, inferior temporal, and lateral occipital regions, has been suggested to play an important role in visual processing of orthographic information (Cohen et al., 2000; Cohen et al., 2002; Dehaene et al., 2002). A variety of evidence suggests that these visual processes are hierarchically organised with componential representations of individual letters and letter sequences in posterior temporal and occipital regions, and more holistic representations of whole words in anterior temporal regions (Dehaene et al., 2005; Taylor et al., 2013). For example, Mechelli et al. (2005) found that posterior fusiform activation was greater for pseudowords than for irregular words such as 'pint', whereas anterior fusiform showed the reverse profile. Likewise, Vinckier et al. (2007) showed a hierarchy of neural representations of letter strings in vOT: more posterior vOT activated for all stimuli (including consonant strings and false fonts), whereas mid- to anterior-fusiform regions were only activated for letter sequences that contained familiar letter combinations. In addition, Seghier et al. (2008) found that adult readers who were slower at reading pseudowords than irregular words showed additional activation in both left inferior parietal and left posterior occipito-temporal cortices, reflecting increased effort in componential reading processes. In contrast slower reading of irregular words was associated with increased activation in left anterior occipito-temporal and left ventral inferior frontal regions. These findings support the idea that posterior fusiform and occipito-temporal cortex process parts of words whereas anterior fusiform processes whole-word forms. Debate continues concerning whether this vOT hierarchy includes brain regions that uniquely contribute to reading (Dehaene and Cohen, 2011), or are shared with other domains in which visual and phonological information is associated, e.g. object naming (Price and Devlin, 2011).

In addition to these posterior occipito-temporal regions, a number of other brain areas have been shown to contribute to componential reading processes, as highlighted by contrasting pseudoword and word reading (see review and meta-analyses by Taylor et al. (2013), Cattinelli et al. (2013)). Pseudoword relative to word reading activates left inferior frontal and precentral gyri, which are involved in phonological output processes, left inferior parietal cortex, which may be involved in mapping letters to sounds, and left posterior occipito-temporal cortex, which may contribute to sub-lexical analyses of written word forms. The reverse contrast of word relative to pseudoword reading, capturing holistic reading processes, activates left middle temporal and angular gyri, regions which may support semantic processing (see Taylor et al. (2013) for discussion).

In summary the componential and holistic processes that underlie reading appear to be supported by different neural systems (holistic reading in anterior vOT regions, componential reading in posterior vOT, inferior parietal cortex, and inferior frontal gyrus). However, as discussed at the outset, the relative role of holistic and componential processes in *learning to read* is not clear. Experimental evidence of the relative contribution of these neural systems in the initial stages of reading instruction might therefore contribute to a scientific understanding of debates between phonic and whole-word approaches to reading acquisition.

1.2. Neural contributions to learning to read

There are two broad methods by which neuroscientists have studied the brain changes associated with the emergence of literacy (see Dehaene et al. (2015) for a review). The first of these is to explore neural activity in children at different stages of learning to read. Activation in vOT to words has been shown in young children in tasks involving sub-lexical processing such as single letter naming (Turkeltaub et al., 2008) and associating letters with sounds (Brem et al., 2010), but also for lexical tasks such as single word reading (Church et al., 2008). Furthermore, a meta-analysis of 40 imaging studies showed that both child and adult readers showed activation in left vOT, inferior frontal, and posterior parietal regions (Martin et al., 2015). However, there were also age-related differences: activation was more consistently observed in posterior fusiform regions for adult than child readers, possibly reflecting increased sensitivity in adults to the differences between letters and control stimuli. Tracking neural changes in a single group of children over four years, Ben-Shachar et al. (2011) showed that the sensitivity of left vOT to written words increased as reading improved, and that this was correlated with sight word naming accuracy but not with measures of pseudoword reading. Furthermore, the spatial extent of the cortical region sensitive to visual words increased as children got older before decreasing until reaching adult level. This changing response may reflect the region initially becoming more engaged for orthographic inputs before later becoming more efficient as specialisation takes place, following an inverted-u shaped profile (Ben-Shachar et al., 2011; Price and Devlin, 2011). Taken together, these results suggest that vOT regions become more sensitive to orthographic information with increased age/proficiency but it is not clear whether this change is linked to holistic or componential reading processes.

Parietal activation in children has primarily been shown in tasks involving mappings between visual words and sounds, (e.g., Bitan et al., 2006, 2007a, 2007b; Cao et al., 2006; Hoeft et al., 2007). For example children making spelling (orthographic) or rhyme (phonological) judgements about visually presented words showed increased activation in bilateral inferior/superior parietal lobules for spelling compared to rhyme judgements (Bitan et al., 2007a). Likewise Hoeft et al. (2007) found that activation in left inferior parietal lobes correlated with composite behavioural measures of phonics ability in children. Further evidence that parietal regions support the componential aspects of reading early in development comes from Cao et al. (2015) who compared adult and child English and Chinese speakers in a visual word rhyming task. Reading skill in English speaking children was correlated with activation in left inferior parietal lobule. The same was not true for Chinese speaking children, lending support to the idea that early reading in English, with its reliance on componential letter-