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Identification of the regions involved in phonological assembly using a novel paradigm

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ABSTRACT

Here we adopt a novel strategy to investigate phonological assembly. Participants performed a visual lexical decision task in English in which the letters in words and letterstrings were delivered either sequentially (promoting phonological assembly) or simultaneously (not promoting phonological assembly). A region of interest analysis confirmed that regions previously associated with phonological assembly, in studies contrasting different word types (e.g. words versus pseudowords), were also identified using our novel task that controls for a number of confounding variables. Specifically, the left pars opercularis, the superior part of the ventral precentral gyrus and the supramarginal gyrus were all recruited more during sequential delivery than simultaneous delivery, even when various psycholinguistic characteristics of the stimuli were controlled. This suggests that sequential delivery of orthographic stimuli is a useful tool to explore how readers, with various levels of proficiency, use sublexical phonological processing during visual word recognition.

1. Introduction

The process of translating orthography into phonology during reading can occur at multiple levels. These levels can differ in the size of the orthographic unit (lexical or sublexical) and the contribution of semantics. For example, once the relationship between sublexical orthography and phonology is learnt, it is possible to read new words or pseudowords (e.g. *blig*) that have no semantic associations. Conversely, words with atypical spellings (e.g. *yacht*) can only be read correctly via previously learnt lexico-semantic associations. These observations motivated dual-route theories of reading (Coltheart, Davelaar, Jonasson, & Besner, 1977; Marshall & Newcombe, 1973; Meyer, Schvaneveldt, & Ruddy, 1974; Morton, 1980), with the sublexical, grapheme to phoneme route being referred to as the 'indirect', 'graphophonological' or 'assembled' route to visual word recognition and the lexico-semantic route referred to 'direct' or 'addressed phonology'. The notion of dissociable routes to phonology is also fundamental to connectionist models that differentially weight the possible links between orthographic and phonological units (Meyer et al., 1974; Plaut, McClelland, Seidenberg, & Patterson, 1996; Seidenberg & McClelland, 1989).

Dissociable brain mechanisms underlying lexical and sublexical reading have been indicated by both lesion and functional imaging studies. Lesion data have shown that some patients have more difficulty reading pseudowords than atypically spelt words (e.g. McCarthy & Warrington, 1986) whereas others show the reverse pattern (e.g. Beauvois & Dérouesné, 1979). Likewise, functional imaging studies have reported greater activation for pseudoword than word reading, with the most consistent effect reported in the pars opercularis of the left inferior frontal gyrus (e.g. Brunswick, McCrory, Price, Frith, & Frith, 1999; Fiebach, Friederici, Müller, & Von Cramon, 2002; Fiez, Balota, Raichle, & Petersent, 1999; Fiez & Petersen, 1998; Hagoort et al., 1999; Heim et al., 2005; Herbster, Mintun, Nebes, & Becker, 1997; Mechelli, Gorno-Tempini, & Price, 2003; Mechelli et al., 2005; Paulesu et al., 2000; Xu et al., 2001). However, it has also been

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observed that the left pars opercularis is more activated for reading words with irregular than regular spellings, with no significant differences between pseudoword and irregular word reading (Fiez et al., 1999; Mechelli et al., 2005; Nosarti, Mechelli, Green, & Price, 2010). As irregularly spelled words cannot be read using a phonological assembly strategy, and both types of stimuli are slower to read than regularly spelled words, these authors suggested that activation in the left pars opercularis might simply reflect processing load (Fiez et al., 1999; Mechelli et al., 2005; Nosarti et al., 2010). In contrast, activation in the left dorsal precentral gyrus has been reported to be higher for pseudoword reading than both regular and irregular word reading (Mechelli et al., 2005; Nosarti et al., 2010). The function of the left dorsal precentral gyrus may therefore play a role that is more specific to phonological assembly than that of pars opercularis.

In addition to the influence of processing load, the comparison of pseudoword to word reading is also confounded by inevitable differences in a range of psycholinguistic variables, specifically: frequency and familiarity (by definition, greater for words than pseudowords), orthographic typicality (i.e. bi- and trigram frequencies, which may, paradoxically, be higher in pseudowords than in low-frequency exception words) and associations to meaning (semantics). Not surprisingly, explicit manipulation of each of these word characteristics also leads to modulation of activation within the word reading network (Carreiras, Mechelli, & Price, 2006;Hauk, Davis, & Pulvermüller, 2008; Woollams, Silani, Okada, Patterson, & Price, 2011).

In order to tease apart the neural systems involved in assembled and addressed phonology more reliably, Mei et al. (2014) developed an artificial language using an orthography that was unfamiliar to their participants. Native English speakers were taught to read words presented in Korean Hangul characters. Two groups of participants were trained to read words written in this artificial language using either addressed or assembled phonology strategies. Participants who were trained to use an assembled phonology approach activated the left inferior frontal gyrus/precentral gyrus and the left supramarginal gyrus more than those trained to read the words using the addressed phonology strategy. As with the pars opercularis, the left supramarginal gyrus has also been identified in a number of previous studies as involved in being phonological processing (e.g. Price, Moore, Humphreys, & Wise, 1997; Sliwinska, James, & Devlin, 2014).

The design of the training study used by Mei et al. (2014) ensured that there were no stimulus differences between the two conditions of interest. However, the use of an artificial language meant that participants read an unfamiliar script. It is unclear whether the reading network recruited during the relatively effortful decoding of an unfamiliar orthographic script can be directly mapped onto the natural reading of a native language in skilled readers.

In the present study, we adopt a novel strategy to investigate phonological assembly within-subjects, using stimuli from their native language. Participants performed a visual lexical decision task in which high-frequency/familiarity concrete nouns (e.g. 'cake', 'mug', 'sock') were contrasted with low-typicality letterstrings (e.g. 'fpzo', 'mwg', 'wpwy'). In addition to focusing our planned analyses on contrasts of word *type*, we also manipulated *delivery form*. Letters within the stimulus items were delivered either sequentially or simultaneously. Thus, we argue, phonological assembly is either promoted in the case of sequential stimuli, or not promoted, in the case of simultaneous stimuli. Although this does not guarantee that the participants would rely on assembled more than addressed phonology for the sequentially delivered stimuli, the visual form information that enables whole word recognition is not available for stimuli delivered sequentially until each letter has been identified. This is not the case for the simultaneously delivered stimuli. Therefore, we hypothesised that sequential delivery, relative to the simultaneous delivery, would highlight the brain regions involved in phonology assembly. The non-static delivery of the stimulus makes reading less natural than reading a normal static script. Nonetheless, a significant advantage of this approach is that we were able to use a within-subject design and the same stimulus identities across both delivery forms, thus controlling for individual variability and holding all linguistic properties of the stimuli constant, in the participants' native language.

We predicted that the sequential delivery of stimuli would result in more activation in parts of the left pars opercularis and supramarginal gyrus that have been associated with using a phonological assembly strategy to read an artificial script (Mei et al., 2014) and the portion of precentral gyrus associated with reading pseudowords more than words with atypical spellings (Mechelli et al., 2005; Nosarti et al., 2010). Furthermore, we tested the hypothesis that these regions would show a lexicality effect (greater activation for words relative to letterstrings), during sequential but not simultaneous delivery of stimuli. Our rationale here was that, during lexical decisions for sequentially delivered items, the demands on visual and phonological memory will be less for letterstrings than words because letterstrings can be rejected as soon as an illegal letter combination is detected, whereas words cannot. Such a finding would indicate that the role of these regions in phonological assembly may be linked to phonological working memory load.

2. Methods

2.1. Participants

Sixteen participants were scanned for this study. All were right-handed, monolingual, native English speakers. All had normal or corrected-to-normal vision and were without any known neurological or behavioural abnormalities. All participants gave informed, written consent to participate in the study, which was approved by the local Research Ethics Committee. Participants were only included in the fMRI analyses if they made fewer than 25% errors in any one condition and fewer than 15% errors across all conditions. Two participants were excluded on this basis. One further participant was excluded due to excessive head motion in the scanner (greater than a voxel = 3 mm). Data from thirteen participants (six women) were included in the analyses. Their mean age was 30 years (range: 18.8–43.8 years). All tested within the normal range on the block design subtest of the WAIS-R (Wechsler, 1981) (mean percentile: 84.15 [S.D. 13.7]; range 63–98). All were good readers (mean reading age: 18.6 years [S.D. 1.6]; range: 15.5–20.5 years; Vernon-Warden Reading Comprehension Test Revised, 1996) with no reported history of dyslexia.

2.2. Experimental design

There were four conditions that orthogonally manipulated lexicality (words vs. letterstrings) and delivery format (sequential vs. simultaneous) resulting in a fully balanced 2 (lexicality) × 2 (delivery format) factorial design (both within subjects factors). Participants made a speeded, forced-choice button-press response to each stimulus item, indicating whether or not the item was a word (visual lexical decision task). For all participants, the right index and middle fingers were used for words and letterstrings, respectively.