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Differential effects of orthographic and phonological consistency in cortex for children with and without reading impairment

Donald J. Bolger[a,b,c,*], Jennifer Minas[a], Douglas D. Burman[a], James R. Booth[a,c,d,*]

[a] Department of Communication Sciences and Disorders, Northwestern University, 2240 Campus Drive, Evanston, IL 60208, USA
[b] Department of Human Development, University of Maryland, College Park, MD 20742, USA
[c] Interdepartmental Program in Neuroscience, Northwestern University, Evanston, IL, USA
[d] Department of Radiology, Evanston Northwestern Healthcare, Evanston, IL, USA

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ABSTRACT

One of the central challenges in mastering English is becoming sensitive to consistency from spelling to sound (i.e. phonological consistency) and from sound to spelling (i.e. orthographic consistency). Using functional magnetic resonance imaging (fMRI), we examined the neural correlates of consistency in 9–15-year-old Normal and Impaired Readers during a rhyming task in the visual modality. In line with our previous study [Bolger, D. J., Hornickel, J., Cone, N. E., Burman, D. D., & Booth, J. R. (in press). Neural correlates of orthographic and phonological consistency effects in children. *Human Brain Mapping*], for Normal Readers, lower phonological and orthographic consistency were associated with greater activation in several regions including bilateral inferior/middle frontal gyri, bilateral anterior cingulate cortex as well as left fusiform gyrus. Impaired Readers activated only bilateral anterior cingulate cortex in response to decreasing consistency. Group comparisons revealed that, relative to Impaired Readers, Normal Readers exhibited a larger response in this network for lower phonological consistency whereas orthographic consistency differences were limited. Lastly, brain–behavior correlations revealed a significant relationship between skill (i.e. Phonological Awareness and non-word decoding) and cortical consistency effects for Impaired Readers in left inferior/middle frontal gyri and left fusiform gyrus. Impaired Readers with higher skill showed greater activation for higher consistency. This relationship was reliably different from that of Normal Readers in which higher skill was associated with greater activation for lower consistency. According to single-route or connectionist models, these results suggest that Impaired Readers with higher skill devote neural resources to representing the mapping between orthography and phonology for higher consistency words, and therefore do not robustly activate this network for lower consistency words.

1. Introduction

Some alphabetic writing systems, such as English, are fairly inconsistent in the mapping between orthography and phonology. Numerous studies have shown that lower phonological consistency, which occurs when the same spelling has different pronunciations (e.g. *seat* versus *sweat*), slows reaction time of adults during lexical decision, naming, and reading tasks in the visual modality (Fiez, Balota, Raichle, & Petersen, 1999; Jared, McRae, & Seidenberg, 1990; Lacruz & Folk, 2004; Stone, Vanhoy, & VanOrden, 1997; Ziegler, Montant, & Jacobs, 1997). Recent work has also shown that lower orthographic consistency, which occurs when a sound can be spelled in multiple ways (e.g. *grade* and *laid*), slows reaction time in adults during lexical decision and naming tasks in the visual modality (Kessler, Treiman, & Mullennix, 2007; Lacruz & Folk, 2004; Massaro & Jesse, 2005; Stone et al., 1997; Ziegler et al., 1997).

A decade-old meta-analysis by Metsala, Stanovich, and Brown, (1998) concluded that the phonological consistency effect was not statistically different in Normal Readers versus Impaired Readers. The mean effect size for the Normal Readers was $d = 0.68$ (95% confidence interval = 0.56–0.80) and the mean effect size for Impaired Readers was $d = 0.58$ (95% confidence interval = 0.46–0.70). They reported that many studies found significant consistency effects of equal magnitude in Normal Readers and Impaired Readers (Baddeley, Logie, & Ellis, 1988; Ben-Dror, Pollatsek, & Scarpati, 1991; Bruck, 1988; Bruck & Treiman, 1990; Holligan & Johnston, 1988; Manis, Szeszulski, Holt, & Graves, 1990; Olson, Kliegl, Davidson, & Foltz, 1985; Stanovich, Nathan, & Zolman, 1988; Szeszulski & Manis, 1987). However, they also reported that

* Corresponding authors at: Department of Communication Sciences and Disorders, Northwestern University, 2240 Campus Drive, Evanston, IL 60208, USA. Tel.: +1 847 491 2519; fax: +1 847 491 4975.
E-mail addresses: d-bolger@northwestern.edu, djbolger@umd.edu (D.J. Bolger), j-booth@northwestern.edu (J.R. Booth).

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some studies found significant consistency effects for both Normal Readers and Impaired Readers that was greater for Normal Readers (Beech & Awaida, 1992; Murphy & Pollatsek, 1994; Siegel & Ryan, 1988; Szeszulski & Manis, 1987), significant consistency effects for Normal Readers but not for Impaired Readers (DiBenedetto, Richardson, & Kochnower, 1983; Frith & Snowling, 1983; Johnston, Anderson, Perrett, & Holligan, 1990; Siegel & Ryan, 1988), and no significant consistency effects for either Normal Readers or Impaired Readers (Beech & Harding, 1984; Treiman & Hirsh-Pasek, 1985). Interestingly, they reported no studies that showed a larger phonological consistency effect for Impaired Readers.

More recent studies have also been inconclusive regarding the consistency effect. Two studies reported differences between Normal Readers and Impaired Readers in learning lower versus higher consistency words. In one study, Chinese dyslexics performed less well than reading-match controls in learning lower phonologically consistent compared to higher phonologically consistent words (Ho, Chan, Tsang, Lee, & Chung, 2006). However, another study with English phonological dyslexics did not show an advantage for learning higher phonological consistency compared to lower phonological consistency words as compared to age- and reading-match controls (Bailey, Manis, Pedersen, & Seidenberg, 2004). To our knowledge, only one study has examined orthographic consistency effects in Normal Readers compared to Impaired Readers. This study found that both dyslexic and control children showed phonological consistency effects in reading and spelling, but only dyslexic children showed orthographic consistency effects in reading, and it was significantly larger than for Normal Readers (Davies & Weekes, 2005). Although the results of previous studies are likely to be contradictory because of differences in languages studied, tasks used and characteristics of the populations, altogether the research suggests that there is a larger phonological consistency effect in Normal Readers compared to Impaired Readers. The limited behavioral research on orthographic consistency prohibits any conclusion regarding group differences.

Neuroimaging studies have shown that phonological consistency is associated with specific brain activity. Studies have found that adults show greater activation for lower phonological consistency words in left inferior frontal gyrus (Binder, Medler, Desai, Conant, & Liebenthal, 2005; Fiez et al., 1999; Herbster, Mintun, Nebes, & Becker, 1997; Katz et al., 2005; Peng et al., 2004; Tan, Feng, Fox, & Gao, 2001), left superior temporal cortex (Peng et al., 2004; Tan et al., 2001) and left inferior parietal cortex (Binder et al., 2005; Peng et al., 2004). Other studies not examining the phonological consistency effect have implicated posterior dorsal inferior frontal gyrus and superior temporal gyrus in phonological processing (Poldrack et al., 1999; Vigneau et al., 2006) and inferior parietal cortex in integrating orthographic and phonological representations (Booth et al., 2002, 2003). Neuroimaging studies also show that lower phonological consistency words produce greater activation in medial frontal gyrus/anterior cingulate cortex (Binder et al., 2005; Tan et al., 2001). Various studies have implicated medial frontal gyrus/anterior cingulate cortex in conflict resolution (Barber & Carter, 2005; Kerns et al., 2004). Finally, only one study has shown a phonological inconsistency effect in fusiform gyrus, but this was limited to low frequency words (Peng et al., 2004). Fusiform gyrus has been implicated in orthographic processing (Cohen, Jobert, Le Bihan, & Dehaene, 2004; Dehaene et al., 2004). However, patient studies suggest that the fusiform gyrus may play a critical role in the phonological consistency effect. Adult patients with damage to posterior inferior temporal cortex (BA 20, 37) have a more severe deficit with spelling lower consistency compared to higher consistency words, and most errors are phonologically plausible (Rapcsak & Beeson, 2004). In addition, a case study in 14-year-old girl with left occipital lesion showed that she was more successful at reading higher consistency than lower consistency words, with most errors involving regularization (Samuelsson, 2000).

Only one imaging study has examined the neural correlates of orthographic and phonological consistency effects in children (Bolger, Hornickel, Cone, Burman, Booth, in press). In the same rhyming task used in the current study, we found both lower orthographic and phonological consistency was correlated with greater activation in left inferior frontal gyrus and bilateral medial frontal gyrus/anterior cingulate cortex. The consistency effects for the rhyming task were greater than the consistency effects for a spelling task, presumably because the former required mapping between orthographic and phonological representations for correct performance but the latter did not. In addition, accuracy was correlated with consistency effects for the rhyming task in left fusiform gyrus. Lower skill children were not sensitive to phonological or orthographic consistency, moderate skill children were only sensitive to lower phonological and orthographic consistency, and high skill children were sensitive to both higher and lower phonological and orthographic consistency. The brain–behavior correlations in fusiform gyrus suggest that children are initially sensitive lower consistency words and only with greater expertise do they become tuned to higher consistency words. More generally, these results are consistent with behavioral studies suggesting that consistency effects are larger in more skilled readers.

Two prominent models of reading have been used to account for consistency effects. Dual-route models (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) postulate a fast lexical route (also referred to as addressed or direct) that associates whole words in an orthographic system to whole words in a phonological system plus a slower, independent sub-lexical route (also referred to assembled or indirect) that contains grapheme (letter)–phoneme (sound) correspondence rules. Dual-route models argue these rules are used for processing unfamiliar words (i.e. low frequency words) and pseudowords that do not have an orthographic or phonological representation. Although the sub-lexical route can also process high frequency words, the faster lexical route typically processes high frequency words, as well as words with lower phonological consistency (i.e. irregular or exception words) because the grapheme–phoneme correspondence rules would generate incorrect pronunciations for these words. In contrast, single-route or connectionist models (Plaut, McClelland, Seidenberg, & Patterson, 1996) argue that there is one mechanism for mapping between orthographic and phonological representations and these models have been used to account for frequency, consistency and pseudoword effects without postulating separate grapheme–phoneme correspondence rules. Some neuroimaging studies have adopted the dual-route approach and have argued that the dorsal system involving inferior parietal and posterior superior temporal cortex is involved in rule-based mapping between orthography and phonology (Pugh et al., 2000). These models predict that this ruled-based system should show greater activation for higher consistency words because these words can be processed with grapheme–phoneme correspondence rules. However, as reviewed above, the literature suggests that temporo-parietal cortex actually shows greater activation for lower consistency words. In contrast, single-route models argue that lower consistency words should produce higher cross entropy values meaning that larger numbers of units of information (i.e. more wide spread activation) are necessary to represent this information. The single-route model is, therefore, more in line with the neuroimaging literature that shows lower consistency words produce greater activation in temporo-parietal cortex.

Our previous study examined orthographic and phonological consistency effects in a large sample of Normal Readers, and whether these effects were correlated with skill. The goal of the current study was to examine differences between Normal Readers