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Orthographic and phonological selectivity across the reading system in deaf skilled readers

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ABSTRACT

People who are born deaf often have difficulty learning to read. Recently, several studies have examined the neural substrates involved in reading in deaf people and found a left lateralized reading system similar to hearing people involving temporo-parietal, inferior frontal, and ventral occipito-temporal cortices. Previous studies in typical hearing readers show that within this reading network there are separate regions that specialize in processing orthography and phonology. We used fMRI rapid adaptation in deaf adults who were skilled readers to examine neural selectivity in three functional ROIs in the left hemisphere: temporoparietal cortex (TPC), inferior frontal gyrus (IFG), and the visual word form area (VWFA). Results show that in deaf skilled readers, the left VWFA showed selectivity for orthography similar to what has been reported for hearing readers, the TPC showed less sensitivity to phonology than previously reported for hearing readers using the same paradigm, and the IFG showed selectivity to orthography, but not phonology (similar to what has been reported previously for hearing readers). These results provide evidence that while skilled deaf readers demonstrate coarsely tuned phonological representations in the TPC, they develop finely tuned representations for the orthography of written words in the VWFA and IFG. This result suggests that phonological tuning in the TPC may have little impact on the neural network associated with skilled reading for deaf adults.

1. Introduction

Learning to read can be challenging for people who are born deaf because they do not have full access to the spoken language encoded by print. Although reading outcomes are generally poor for deaf individuals, some deaf people do nonetheless achieve high levels of reading proficiency (Qi and Mitchell, 2012; Traxler, 2000). Numerous studies have examined reading in people who are deaf, yet to date there is no clear agreement of what contributes to these reading difficulties and why some deaf people are good readers and others are not. One theory is that those who are able to develop age-appropriate reading skills have strong phonological skills and are able to make strong connections between orthography and phonology (Mayer and Trezek, 2014). These authors purport that phonology is essential to reading regardless of hearing status. While a role for phonology in reading success for deaf individuals might make sense based on our understanding of reading in the hearing population, a recent meta-analysis showed that phonological skills account for only 11% of the variance in reading ability for deaf people. However, language ability accounts for 35% of the variance, making it a better predictor of reading skill (Mayberry et al., 2011).

Currently, little is known about the neural architecture supporting reading in deaf people, or the ways the brain responds and adapts to support reading when auditory input is limited (and thus access to phonology is restricted); nonetheless, several recent studies have shed some light on the neural underpinnings of reading in deaf adults (Corina et al., 2013; Emmorey et al., 2013, 2016; Wang et al., 2015). In order to situate those recent neuroimaging studies, we first briefly review the literature on hearing readers.

Over the past two decades understanding the neural components of reading in hearing children and adults has received much attention. As such, we have a better understanding of the neural circuitry involved in visual word recognition in the hearing population. Recent research has focused on three main neuroanatomical regions involved in single word reading: the occipitotemporal cortex (OTC), temporoparietal cortex (TPC), and inferior frontal gyrus (IFG; e.g., Carreiras et al., 2014). These studies provide evidence for a hierarchical organization in the ventral visual OT pathway for visual word form, leading to the proposal that,

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running posteriorly to anteriorly along this pathway, neurons are tuned to increasingly complex word features, namely from oriented bars, to letters, bigrams, and finally to quadragrams (Cohen and Dehaene, 2004; Vinckier et al., 2007). Glezer et al., (2009, 2015, 2016) provided evidence that an area within the ventral OT (vOT) region, the so-called visual word form area (VWFA), appears to function like an orthographic lexicon. Neurons in this part of the brain seem to be specialized to process written words we have learned, and not novel words. Additionally, this selectivity appears to be specific to the left hemisphere, as the homologous right hemisphere VWFA does not show this same selectivity (Glezer et al., 2015).

Although it is agreed that the VWFA is involved in reading, there have been conflicting reports about the specificity of this area, and it has been debated whether the OTC might also be involved in aspects of reading that go beyond just the visual /orthographic processing of words. A number of studies have shown that the vOT is activated when people engage in a host of language tasks and processes including (but not limited to) pseudoword rhyming and reading (Dietz et al., 2005; Hagoort et al., 1999, Xu et al., 2001), naming familiar pictures, reading Braille, processing auditory and tactile words (Price and Devlin, 2003, 2004), and processing phonological information (Price and Devlin, 2011; Twomey et al., 2011; Yoncheva et al., 2010). Activity in this region has also been shown to be modulated by top down processing and task demands (Hellyer et al., 2011; Kherif et al., 2011). Interestingly, a study by Glezer and Riesenhuber (2013) found that when identified at the individual subject level, the VWFA shows selectivity for written words, but when the VWFA is defined at the group level, intersubject variability in the location and size of the VWFA causes this selectivity to be washed out. This result suggests that many of the conflicting findings may be accounted for by the type of analysis conducted.

In hearing readers, both TPC and IFG have been implicated in phonological and semantic aspects of written word reading (Binder et al., 2009; Katzev et al., 2013; Kircher et al., 2011); however, the exact nature of the processing that occurs within these regions is controversial. A recent meta-analysis sought to reconcile some of the conflicting findings (Vigneau et al., 2006). Vigneau et al. showed that both TPC and IFG have clusters of neurons that independently respond to semantics and phonology, as well as other clusters that respond to both, suggesting that single- and mutli-domain processing occurs in these regions. However, the exact nature of the representations processed in these areas during word reading is still unclear. Recently, Glezer et al. (2016) showed that a region within the TPC appears to be finely tuned to phonological features during single word reading in typical hearing readers, and that this same region shows weak selectivity to phonological features in people with dyslexia (Glezer et al., 2018). These findings suggest that a region within the TPC does indeed engage in phonological processing during word reading, and moreover, that it shows altered tuning in hearing people with reading difficulties.

A number of fMRI studies have focused on the neural correlates associated with different levels of reading skill in hearing people, most notably in the area of dyslexia (Boets et al., 2013; Hasko et al., 2013; Mahé et al., 2013; Richlan et al., 2011; Sun et al., 2010; van der Mark et al., 2009). As mentioned earlier, a few recent studies examined the neural circuitry of reading in deaf adults (Aparicio et al., 2007; Corina et al., 2013; Emmorey et al., 2013, 2016; Wang et al., 2015). Generally, these studies indicate that skilled deaf readers engage a neural circuitry similar to that reported for hearing readers, particularly when engaged in semantic tasks. However, it appears that reading skill level and type of task (i.e., phonological vs. semantic) both modulate activity in the reading circuit for this population, suggesting different processing strategies as a function of skill and linguistic processing requirements. In regions known to be involved in skilled reading (IFG, TPC, VWFA) for hearing people, results have been mixed as to whether these regions are similarly engaged for deaf readers. We outline the findings for each of these regions below.

1.1. IFG

The results regarding the role of the IFG during reading in deaf people are inconclusive. While some results show that the IFG is differentially engaged in deaf versus hearing readers, other findings indicate the IFG is similarly active for both groups. Evidence for differential engagement comes from Aparicio et al. (2007), who showed that deaf readers, when engaged in a phonological task, activated the left and right IFG more than hearing readers. Additionally, they showed that hearing people activated the left IFG more and deaf people activated the right IFG more during a lexical decision task. However, one thing to note is that these differences may be due to the fact that the deaf group had a lower reading level than the hearing group. Controlling for reading level, Emmorey et al. (2013) showed that both deaf and hearing readers activated the left IFG during a semantic task (concreteness judgment) and a phonological task (syllable counting). However, when comparing the tasks directly, within each group, they found that the deaf group showed more activation in the left IFG for the semantic task than the phonological task, whereas the hearing group did not. This result suggests that while deaf readers are employing the same neural circuitry for reading as hearing people, the type of task has an impact on degree of activation, particularly when phonological processing is required. Emmorey et al. (2013) suggest deaf readers may be less likely than hearing readers to activate phonological representations when performing a semantic task (and vice versa for a phonological task). There are also mixed results concerning whether reading skill level affects activation in the IFG in deaf readers. Corina et al. (2013) reported that both proficient and less proficient readers activated the IFG during an implicit reading task, whereas Emmorey et al. (2016) found that during a semantic task the left IFG is activated more for skilled deaf readers compared to less skilled readers.

1.2. TPC

Temporoparietal cortex findings are also quite mixed. While Aparicio et al. (2007) found more activation for deaf than hearing readers in the TPC region during a lexical decision task, Emmorey et al. (2013) did not observe a difference between groups during a semantic decision task. One fairly consistent finding, however, is that during phonological tasks, parietal regions within the TPC (inferior parietal lobule and supramarginal gyrus) are more active for deaf compared to hearing readers (Aparicio et al., 2007; Emmorey et al., 2013; Li et al., 2014). This result would suggest that, similar to the IFG, the type of task can affect activation in the TPC. One other consistent finding is that another region within the TPC, very near the TPC region of interest (ROI) used for the present study, activates more for skilled compared to less skilled deaf readers (Corina et al., 2013; Emmorey et al., 2016).

1.3. VWFA

Results from studies of deaf readers are fairly consistent regarding VWFA activation. Generally, researchers have found no differences in VWFA activation between deaf and hearing readers (Aparicio et al., 2007; Emmorey et al., 2013; Wang et al., 2015). However, there are mixed results when comparing between skill levels. Corina et al. (2013) found greater activation for more proficient deaf readers, while Emmorey et al. (2016) found no difference between skilled and less skilled deaf readers in this region. Furthermore, Wang et al. (2015) examined how lack of auditory input in profoundly deaf readers impacts the location and functional connectivity of the VWFA and found that the location and extent of activation were similar between the deaf and hearing groups, but deaf readers showed reduced functional connectivity between vOT cortex and superior temporal cortex.

Preferential functional connectivity between the VWFA and TPC has been shown in the hearing population, and the strength of this connectivity predicts performance on a semantic reading task (Stevens