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# The N170 ERP component differs in laterality, distribution, and association with continuous reading measures for deaf and hearing readers

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The temporo-occipitally distributed N170 ERP component is hypothesized to reflect print-tuning in skilled readers. This study investigated whether skilled deaf and hearing readers (matched on reading ability, but not phonological awareness) exhibit similar N170 patterns, given their distinct experiences learning to read. Thirty-two deaf and 32 hearing adults viewed words and symbol strings in a familiarity judgment task. In the N170 epoch (120–240 ms) hearing readers produced greater negativity for words than symbols at left hemisphere (LH) temporo-parietal and occipital sites, while deaf readers only showed this asymmetry at occipital sites. Linear mixed effects regression was used to examine the influence of continuous measures of reading, spelling, and phonological skills on the N170 (120–240 ms). For deaf readers, better reading ability was associated with a larger N170 over the right hemisphere (RH), but for hearing readers better reading ability was associated with a smaller RH N170. Better spelling ability was related to larger occipital N170s in deaf readers, but this relationship was weak in hearing readers. Better phonological awareness was associated with smaller N170s in the LH for hearing readers, but this association was weaker and in the RH for deaf readers. The results support the phonological mapping hypothesis for a left-lateralized temporo-parietal N170 in hearing readers and indicate that skilled reading is characterized by distinct patterns of neural tuning to print in deaf and hearing adults.

## 1. Introduction

Reading is an essential skill of modern life that most citizens of industrialized countries master by late adolescence. However, the apparent ease with which the majority of children become fluent expert readers is somewhat deceiving – decades of research has shown that the neuro-cognitive processes involved in acquiring and then using this skill are extremely complex (e.g., Rayner et al., 2001). Although a full specification of the processes involved in reading and learning to read is still lacking, it is clear that a highly coordinated and rapid interplay of sensory, perceptual and linguistic processes all play a role.

Perhaps one factor contributing to the apparent ease of learning to read is the fact that many aspects of the skill are built on top of a preexisting and well-developed system of spoken language comprehension. It is therefore not surprising that theories of reading usually reserve a primary role for prior spoken word knowledge in the mechanics of learning to read as well as skilled adult reading (e.g., Frost, 1998). For hearing people, weak phonological skills are clearly linked to poorer reading ability in both children (e.g., Wagner and Torgesen, 1987) and adults (e.g., Macaruso and Shankweiler, 2010). Whether phonological skills are similarly critical to reading success for deaf individuals is currently under intense debate. Some argue that the process of learning to read is essentially the same for deaf and hearing children and that speech-based phonological skills are key to reading achievements for both groups (Easterbrooksetal., 2008; Paul et al.,2009; Perfetti and Sandak, 2000; Wang et al., 2014). Others have recently argued that phonology does not play a central role in the development or maintenance of skilled reading for deaf people (Mayberry et al., 2010; Miller and Clark, 2011). Mayer and Trezek (2014) maintain that interpreting this current research as suggesting a lack of importance for phonology is flawed because these studies were conducted with deaf readers who had not achieved reading success – perhaps because they had not developed strong phonological skills. To address some of these issues, the current study specifically targeted skilled adult deaf readers who are matched on reading level with their hearing peers, with both groups exhibiting a similar range of reading ability. Specifically, we will be interested in examining how deaf and hearing readers differ in the temporal dynamics of reading and what linguistic factors (reading

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ability, spelling skill, phonological awareness) impact these neural patterns.

Critical to all theories of reading is the specification of the neurocognitive processes involved in comprehending the elemental units of written language – visually encountered words. For over 50 years researchers have sought to elaborate the cascade of processes underlying our ability to rapidly recognize and comprehend visually presented words. The speed at which words are comprehended is perhaps one of the most remarkable aspects of reading – during typical reading we recognize between two and five words per second, which puts an upper bound on speed of recognition at 200–500 ms per word. Clearly, to track the rapid time-course of the processes underlying visual word recognition requires a methodology with high temporal resolution. Event-related potentials (ERPs) offer this kind of precision, showing sensitivity to differences in processing at the millisecond level (Luck, 2005).

A substantial body of research using ERPs has shown that this technique is sensitive to a cascade of sensory, perceptual and linguistic processes that unfold over the course of recognizing a word. While the largest group of studies have tended to focus on processes near the end of the recognition stream – in particular those involved in the processing of word meaning (e.g., the N400), more recently a growing number of studies have focused on the earliest perceptual mechanisms involved in processing the orthographic and phonological attributes of words (see Maurer and McCandliss, 2008, for a review). One line of research of particular relevance to the current study is a growing number of reports concerned with the response of a brain region hypothesized to underlie the initial processing of visually presented words – the so-called visual word form area (VWFA; Cohen and Dehaene, 2004). This region is generally localized in functional imaging studies to the left fusiform gyrus and has been shown in fluent adult readers to be significantly more active during the processing of visually presented words and word-like letter strings than to other classes of visual stimuli (Baker et al., 2005; Dehaene and Cohen, 2011). Recent fMRI studies with deaf readers indicate that the anatomical location and activation strength of the VWFA is similar for deaf and hearing adult readers, despite differences in reading skill and phonological awareness between these groups (Aparicio et al., 2007; Emmorey et al., 2013; Wang et al., 2014). However, it is unknown whether activation within the VWFA involves a different time course of visual word recognition for deaf compared to hearing readers.

Of direct relevance to the current study, an even larger literature has shown that an early ERP component peaking around 170 ms after a visual stimulus (the N1 or N170) shows a similar sensitivity to word and word-like stimuli. Specifically, visual words and word-like letter strings produce a larger N170 amplitude than do size and luminance matched visual stimuli from other categories (Maurer and McCandliss, 2008). Moreover, consistent with the fMRI VWFA effect, the N170 to visual words tends to be proportionally larger in amplitude over left hemisphere temporo-occipital scalp sites. One hypothesis concerning the functional significance of the N170 is that it reflects expertise in a particular domain of knowledge representation (Rossion et al., 2003). This notion comes from the observation that a family of N170 effects are seen across a variety of stimulus domains including words, faces, and some non-face objects (Rossion et al., 2003). What typically distinguishes these different varieties of N170 is their scalp distribution. So, while the word-based N170 is larger over left temporo-occipital scalp sites, the face-specific N170 has been shown to have either a more bilateral distribution or slightly right hemisphere predominance. In both cases the idea is that these areas are somehow "tuned" to preferentially process a specific domain of knowledge over the course of massive experience (in the case of words and reading) or perhaps from a combination of experience and evolutionary selection pressure (in the case of faces; Rossion et al., 2003).

With respect to words and the N170, one question that arises is what kind of knowledge and/or perceptual processing reflects the specialization of this component? A variety of studies seem to converge on the possibility that this component is very sensitive to the differential activation of orthographic knowledge. Consistent with this hypothesis, Bentin et al. (1999) – in one of the first studies to systematically examine early visual correlates of letter and word perception using the fine temporal precision of ERPs – reported that an temporo-occipital negativity peaking at 170 ms (N170) differentiated words, pseudowords and letter strings (orthographic stimuli) from strings of alphanumeric symbols (non-orthographic stimuli). While orthographic strings produced a larger left hemisphere N170, symbols strings tended to produce larger N170 activity over the right hemisphere. Numerous subsequent studies have interpreted the larger left hemisphere N170 to words as reflecting the expertise that adult readers have acquired from their substantial exposure to print (e.g., Brem et al.,2005; Cohen et al., 2000; Maurer et al., 2005b; Tarkiainen et al., 1999). More recently Maurer and colleagues (Maurer et al., 2005a, 2005b, 2006, 2007) have argued that the orthographic (letters) vs. non-orthographic (symbols) lateralization differences reflects an acquired differential sensitivity of left temporo-occipital brain regions to "coarse" tuning for print. In other words, during the process of becoming a skilled reader circuits in the left temporo-occipital region stabilize on the combination of features that make up letters. Consistent with this hypothesis Maurer et al. (2005b, 2006) found that children just prior to learning to read (while in kindergarten) did not show the adult pattern of left-lateralized N170 activity (in contrasts of letter string and symbol string stimuli). However, less than two years later when those same children were again tested during the second grade, a pattern more like that found in adults was present. In other words, second graders showed a larger left hemisphere N170 to letters strings than symbol strings. In contrast, "fine-tuning" for print, reflected by sensitivity to regular orthographic structure (e.g., N170 response to words > pseudowords > consonant strings) appears to develop later, possibly not until after 5th grade (Coch and Meade, 2016).

To our knowledge, no previous study has examined the nature or scalp distribution of the N170 to words and symbol strings in deaf readers, and there has been very little electrophysiological research investigating visual word recognition in the deaf population. An early study by Neville et al. (1982) found that congenitally deaf signers did not exhibit visual field asymmetries when reading English words, although their word recognition accuracy was equal to the hearing participants. In the hearing readers an early negativity over occipital regions (N200) was observed which was larger in the hemisphere contralateral to visual field presentation, but for deaf participants this response was symmetric for right visual field (RVF) presentations (and larger in the right hemisphere for left visual field (LVF) presentations). In addition, the response over anterior temporal regions (N160) was larger in the left hemisphere for hearing participants, but was symmetrical for deaf participants. The reading levels of the deaf and hearing groups in this study are unknown, and it is unclear whether the lack of hemispheric asymmetry in both the behavioral and ERP responses for the deaf participants reflects differences in reading skill, phonological ability, or neural reorganization arising from congenital deafness and/or sign language knowledge.

More recently, MacSweeney et al. (2013) contrasted ERP responses in deaf and hearing adults as they performed rhyme judgments to sequentially presented written words (e.g., *chair/bear* pairs in which the rhyme decision could only be made using phonological knowledge). Only data from deaf participants who performed above chance ($n = 9$) were analyzed (hearing participants were at ceiling). MacSweeney et al. (2013) observed no significant group differences in laterality for ERP responses to the first word in the pair (the "contingent negative variation" response between 600 and 1200 ms), although the left laterality effect was significant for the subgroup of nine hearing participants ($p < .01$), and this effect was only a trend for the deaf participants ($p = .083$). Both deaf and hearing participants showed greater negativity to nonrhyming than rhyming pairs between 300–600 ms, with a similar