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Hemispheric specialization for visual words is shaped by attention to sublexical units during initial learning

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ABSTRACT

Selective attention to grapheme–phoneme mappings during learning can impact the circuitry subsequently recruited during reading. Here we trained literate adults to read two novel scripts of glyph words containing embedded letters under different instructions. For one script, learners linked each embedded letter to its corresponding sound within the word (grapheme–phoneme focus); for the other, decoding was prevented so entire words had to be memorized. Post-training, ERPs were recorded during a reading task on the trained words within each condition and on untrained but decodable (transfer) words. Within this condition, reaction-time patterns suggested both trained and transfer words were accessed via sublexical units, yet a left-lateralized, late ERP response showed an enhanced left lateralization for transfer words relative to trained words, potentially reflecting effortful decoding. Collectively, these findings show that selective attention to grapheme–phoneme mappings during learning drives the lateralization of circuitry that supports later word recognition. This study thus provides a model example of how different instructional approaches to the same material may impact changes in brain circuitry.

1. Introduction

Success in early reading acquisition depends on a learner's ability to master the association between spoken words and their corresponding visual word forms. When learning these mappings, a student may attend to individual letters and link them to sounds within a word, thus focusing on sublexical grapheme–phoneme mappings. Alternatively, the budding reader might attend to larger *grain sizes*, such as letter clusters, onsets, rimes, or even whole words (Ziegler & Goswami, 2005). Reading development theories concur that gaining robust grapheme–phoneme connections is vital for achieving reading proficiency (Ehri, 1991; Frith, 1985; Gough & Juel, 1991). In addition to promoting the refinement of known word representations (Perfetti, 1991), proficiency in manipulating attained grapheme–phoneme associations serves as a crucial self-teaching device, which enables beginning readers to decode novel words that they have not encountered previously (Share & Stanovich, 1995). Overall, relative to approaches that promote memorization of the spelling patterns of entire words, sublexical phonics-based strategies yield superior reading acquisition outcomes according to behavioral cognitive psychology meta-analyses (e.g., Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001) and systematic investigations of curriculum effects (e.g., Ehri, Nunes, Stahl, & Willows, 2001).

Reading instruction has valuable potential for directing a student's attention to representations at grain sizes that bolster the acquisition of reliable alphabetic and word knowledge (McCandliss, Beck, Sandak, & Perfetti, 2003). The need for specific attentional guidance during learning is highlighted by the fact that, upon viewing a word, this gamut of grain sizes is available – all at once – to a beginning reader. Additionally, although grapheme–phoneme decoding is typically advantageous, skilled reading of exception words, which cannot be decoded, requires fluent switching between grain sizes. Given the central role of grapheme–phoneme conversion for masterful reading, intentionally directing attention to sublexical specifically *subsyllabic* mappings might be an essential component of a learner's emerging decoding skills (McCandliss & Yoncheva, 2011). The brain mechanisms of this process remain largely unexplored yet are pivotal to understanding how instructional strategies can best be harnessed to support the development of the perceptual expertise for reading (McCandliss, 2010).

Skilled reading engages specialized brain processes allowing rapid categorization of orthographic input as language. One of the earliest print-sensitive responses indexed in the event-related potential (ERP) is the N170 visual word effect, typically characterized as greater occipito-temporal negativity within 200 ms of

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viewing a word relative to a visually matched control stimulus. This N170 response temporally coincides with the time-window that reflects initial word recognition in eye movement studies (for review, see Posner & McCandliss, 1993). The educational experience of learning to read one's own language is crucial for the tuning of the N170 effect to the specific properties of one's native script. Language-specific effects in the perceptual expertise for visual words have been reported in literate adults when reading a known, relative to an unfamiliar, script in another language (Wong, Gauthier, Woroch, DeBuse, & Curran, 2005). Similarly, specific educational impact is evident in pre-literate children who progress through their literacy training to eventually exhibit native script sensitivity, characteristically left-lateralized as in skilled adult readers (Brem et al., 2009). Studies examining the visual word N170 response throughout reading skill accruement often report accompanying modulations of later ERP components (Brem et al., 2006; Brem et al., 2009; Maurer, Blau, Yoncheva, & McCandliss, 2010). These include the N400 component, thought to reflect deeper semantic processing as commonly revealed by comparing expected with unexpected sentence endings (Kutas & Federmeier, 2011), and the Late Positivity Complex (LPC) family of components often attributed to domain-general engagement of learning, attention, and memory functions (Polich, 2007). In the context of reading, LPC effects can be sensitive to old/new word recognition (Friedman, 1990) and explicit/implicit memorization effects frequently observed under repeated word presentation (Rugg et al., 1998). Either or both phenomena might be relevant to emergent decoding skills.

Orthographic (e.g., Dehaene & Cohen, 2011) as well as phonological processes (e.g., Vigneau et al., 2006) are predominantly left-lateralized in fluent readers (for review, see Schlaggar & McCandliss, 2007). Moreover, across individuals the left lateralization of reading-related activations is tightly coupled with the left lateralization of activations linked to speech perception (Pinel & Dehaene, 2010). Visual and spoken word lateralization are also systematically influenced by both genetic and environmental factors (Pinel et al., 2014). Importantly, selective attention to language can engage this left-lateralized integrated network in a purely *top-down* fashion in skilled readers: in the absence of visual input, phonological computations recruit the visual word form area yet acoustic non-linguistic judgments on this same word pair do not (Yoncheva, Zevin, Maurer, & McCandliss, 2010). Furthermore, selective attention to phonology can shape perception by modulating processes as early as online stimulus encoding via transient, temporally specific engagement of orthographic and phonological regions within the left hemisphere (Yoncheva, Maurer, Zevin, & McCandliss, 2014). Such attentional processes may influence neural circuitry during initial learning and thus impact later word recognition. Thus the exact relation between such modulations and learning beckons direct investigation within an approach that combines educational manipulations, learning, and functional brain imaging.

1.1. The current study: approach, questions, and hypotheses

Motivated by accumulating evidence that selective attention to grapheme–phoneme mappings dynamically recruits left-lateralized linguistic processes, the present ERP study addressed questions central to a beginner's grapheme–phoneme (GP) decoding during reading. Early reading acquisition was modeled in a well-controlled paradigm training literate, adult English speakers to read artificial scripts. This manipulation allowed us to investigate – in relative isolation from other, typically confounded factors (e.g., ongoing print exposure, stimulus properties, training time, and a learner's preexisting attentional biases) – how attentional focus shapes subsequent reading responses. Two artificial scripts were created: a GP script, in which each grapheme mapped consistently onto a single phoneme, and another, whole-word (WW) script, in which the pairing between individual graphemes and corresponding phonemes was arbitrary across training trials. Any putative incidentally acquired knowledge of particular letter-sound associations in the WW script was therefore not generalizable to decoding transfer (not previously trained) words, forcing learners to further attend to WW-level mappings. Training was implemented by concurrent presentation of frequent, single-syllable spoken English words and their corresponding artificial script representations. Following training, each learner completed a reading verification task while we recorded their behavioral and ERP responses.

First, we tested the hypothesis that GP decoding engages left-lateralized processes and examined the time-course of this visual word ERP modulation. The theoretical focus of this paper, the left-lateralized N170 effect, is linked more closely to overall script familiarity rather than knowledge of particular visual word forms (Yoncheva, Blau, Maurer, & McCandliss, 2010); therefore we anticipated decoding-related ERP modulations to manifest *after* the initial perceptual categorization indexed by the N170 component, while active decoding processes were at play, e.g., during the N400 or the LPC ERP components. Second, we examined how attending to GP mappings during learning biases a learner's subsequent reading. Response latencies were studied first focusing on trials where a visual word did not match the concurrent single-syllable auditory word. Contrasting latencies during verification of syllable onsets (i.e., initial consonant) relative to syllable rimes (i.e., central vowel and final consonant) provided a behavioral assay likely reflective of decoding processes. To more directly link observed effects to the impact of attentional focus on GP grain sizes, behavioral and visual ERP responses to words trained under GP focus were contrasted with responses to words trained under WW focus, since the two training conditions were equated for total exposure and learning time. We expected to find reading expertise effects, indexed by a left-lateralized N170 response, only when the same student read the script learned under selective focus to GP mappings and not under WW focus. Capitalizing on high-density recordings to capture ERP topographic differences and on Bayesian statistics to temporally localize attentional effects, we carried out data-driven analyses unconstrained by *a priori* assumptions and examined the duration and persistence of effects throughout and following the N170 component.

2. Materials and methods

2.1. Participants

Native English-speaking, right-handed (Oldfield, 1971) volunteers were recruited for the study. Each participant was neurologically healthy with normal hearing and normal, or corrected-to-normal, vision, and was screened for reading disability and prior knowledge of logographic scripts, such as Chinese. To ensure that every subject attended to the training and showed learning progress, accuracy greater than 85% on the average of the two training conditions in the final test of trained words on day 1 was required to invite participants for the second day session, which included the EEG recording (two subjects did not reach criterion). Further, two additional subjects did not meet the ERP data quality criterion detailed in 3.2. ERP preprocessing. Data from 16 participants (mean age: 21.7 years, range: 18–31; 8 women) are reported here. Ethical approval was granted by the Institutional Review Board of Vanderbilt University. All subjects were fully briefed and provided written informed consent.

2.2. Training in artificial orthography

2.2.1. Procedure

Each participant learned to associate sets of auditory words with corresponding visual characters under two training