Hemispheric lateralization in visual word processing : evidence from ERP

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2019

Lau, F. (2019). Hemispheric lateralization in visual word processing : evidence from ERP.
Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/88881>

<https://doi.org/10.32657/10356/88881>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

SINGAPORE

**HEMISPHERIC LATERALIZATION IN VISUAL
WORD PROCESSING: EVIDENCE FROM ERP**

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SCHOOL OF HUMANITIES
2018**

Hemispheric Lateralization in Visual Word Processing: Evidence from ERP

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School of Humanities

A thesis submitted to the Nanyang Technological University in
partial fulfilment of the requirement for the degree of
Doctor of Philosophy

2018

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ACKNOWLEDGEMENTS

While my name may be the only one printed on the cover of this thesis, there are many people without whom this thesis would not have come to fruition. First and foremost, I must thank my thesis supervisor, Dr. Alice Chan, for her unwavering support and guidance, tracing back all the way to my undergraduate days when I did my Final Year Project under her supervision. Dr. Chan was always insightful, approachable, and understanding, and I count my lucky stars for having such a great supervisor.

I would also like to thank my co-supervisor, Dr. KK Luke, and thesis advisory committee members: Dr. Francis Wong and Dr. Justin Dauwels, as well as Dr. Xu Hong for their valuable advice, especially during the early piloting stage of this thesis.

My heartfelt gratitude goes to my fellow lab members, past and present, at the Neurolinguistics and Cognitive Science Lab at NTU: Kastoori, Sophia, Samantha, Wendy, Joey, Yvonne, Edwin, Galston, and April, for their company in this arduous PhD journey, and especially for their comments and suggestions on my work. I'd like to specially thank Sophia for her helpful comments on earlier versions of this thesis, and for believing in me when I did not believe in myself.

They say it takes a village to raise a child. I'm thankful for my MR Village family, my best friends from JC, for keeping me grounded and for growing up with me. I'd also like to thank my housemates, Shiwei, Andreas, Shirley, and Xinwen for making

life in the village that is Jurong West exciting and full of warmth. The biggest thank you goes to my roommate and best friend, Ka Lon, for being always encouraging and supportive.

Saving the best to the end, I would like to thank my family for nurturing me and granting me the freedom to pursue my own interests, and not once pressured me to “find a proper job” as some other parents would. I’d like to specially thank my aunt who took me in when I moved to Singapore at a tender age of 8, for loving me and caring for me as her own.

Lastly, I would like to thank the Linguistics and Multilingual Studies Division at NTU for the extremely rewarding undergraduate and postgraduate programs which have continuously fueled my passion for language research. I would also like to acknowledge the NTU Research Scholarship for the financial support during the course of my study.

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Abstract

Hemispheric lateralization differences between alphabetic and logographic scripts in the occipitotemporal region are well-documented in the literature. The N170 ERP component, which has been source-localized to the occipitotemporal region, is typically left-lateralized for alphabetic scripts, and bilateral or even right-lateralized for logographic scripts. Such cross-linguistic N170 lateralization differences have been explained in terms of visuoperceptual and phonological processing demands, with the former citing distinctions in spatial configuration and visual complexity, and the latter quoting differences in orthographic depth and phonological mapping. At present, the functional significance of N170 lateralization in visual word processing remains an open question and continues to receive substantial research interest.

The two studies in this thesis together investigated if N170 laterality is modulated by visuoperceptual and/or phonological mapping demands. Study One featured an artificial language training paradigm that aimed to uncover how spatial configuration and orthographic transparency shape N170 laterality independently and interactively. Findings demonstrated strong spatial configuration effects on N170 laterality at both pre- and post-training, such that the N170 was left-lateralized for linear configurations and bilateral for square configurations. The effects of orthographic transparency, on the other hand, were not significant. Study Two primarily investigated the coarse (orthographic stimuli vs. visual control) and fine (further distinctions within orthographic stimuli) N170 (commonly referred to as N1 in the print tuning literature) print tuning effects documented in the literature. Coarse N1 print tuning effects were

observed, where orthographic stimuli elicited more left-lateralized responses than non-orthographic stimuli. Although fine N1 print tuning effects did not emerge to be significant in the primary analysis, retrospective analysis within each individual hemisphere found greater negativity for words and pseudowords compared to nonwords only in the left hemisphere, suggesting that the left hemisphere is sensitive to orthographic regularity. Effects of spatial configuration were replicated in Study Two with the inclusion of familiar orthographic stimuli and alphanumeric symbols, reflecting the robustness of spatial configuration effects on N170 lateralization. Study Two further revealed that the spatial configuration effects mainly stemmed from a left hemisphere preference for linear over square stimuli.

In light of the robust visuoperceptual effects and relatively weak phonological mapping effects observed, the findings in this thesis favor the notion that the N170 lateralization in visual word processing is mainly driven by hemispheric visuoperceptual processing capacities, particularly in the left hemisphere. The left hemisphere exhibited a preference for linear stimuli, as well as a sensitivity to well-formed orthographic strings, which may have arisen from general statistical learning mechanisms. In contrast, the right hemisphere demonstrated heightened activity for symbols. Considering the close relationship between phonology and orthography especially in alphabetic scripts, this thesis puts forth an alternative view that phonological mapping processes exert influence over N170 lateralization indirectly, through the shaping of orthographic regularity.

Chapter 1:

Introduction

Written language is a fairly new cultural creation in the history of human development compared to spoken language, and we are still in the midst of understanding how the human brain processes written words. About two decades ago, Cohen et al. (2000) first proposed the existence of a “Visual Word Form Area” (VWFA) within the left occipitotemporal region (OT). In their functional Magnetic Resonance Imaging (fMRI) study, the VWFA was found to be consistently activated when subjects viewed words. More importantly, the VWFA activated more strongly for orthographic stimuli (i.e., letter strings) than for non-orthographic stimuli (e.g., false fonts, fixation). This sensitivity to orthographic stimuli suggests that the VWFA is critically, or specifically, involved in visual word processing. The left OT’s involvement in reading has also been highlighted in Event-Related Potential (ERP) studies. The N170 (also referred to as N1) is an ERP component that originates from the occipitotemporal region (Maurer, Brem, Bucher, & Brandeis, 2005.; Rossion, Joyce, Cottrell, & Tarr, 2003). It is a general indicator of visual expertise which increases in magnitude when one gains extensive experience with a visual category (e.g., higher (more negative) amplitudes when bird experts are looking at birds (Tanaka & Curran, 2001)). Crucially, the N170 topography for orthographic stimuli is typically left-lateralized, as opposed to bilateral or right-lateralized topographies for symbols, objects, and faces (Rossion, Joyce, Cottrell, & Tarr, 2003). Taken together, these initial neuroimaging evidence suggested that the processing of written language is left-lateralized, as with most other language functions (e.g., spoken word production and comprehension).

Intriguingly, as studies accumulated, it became apparent that the left-lateralization in visual word recognition is far less consistently reported as opposed to those reporting on other language functions. This inconsistency was primarily driven by reports of bilateral (e.g., Liu, Dunlap, Fiez, & Perfetti, 2007; Tan, Feng, Fox, & Gao, 2001; Wu, Ho, & Chen, 2012) or even right-lateralized (Tan et al., 2000) activity in the OT for non-alphabetic orthographies as Chinese and Japanese Kanji (commonly referred to as logographic scripts). In contrast, the reading of alphabetic scripts is almost always left-lateralized in the OT (e.g., Cohen et al., 2002; Price, 2012; Vigneau et al., 2005). These cross-linguistic differences were summarized in several fMRI meta-analyses which concluded that the reading of non-alphabetic scripts engages the right homologue of the VWFA to a larger extent, compared to the reading of alphabetic scripts (Bolger et al., 2005; Tan et al., 2005; Wu, Ho, & Chen, 2012). Similarly, in ERP studies, left-lateralized N170 activity is also less consistently reported for the reading of non-alphabetic than alphabetic scripts (Chen, Bukach, & Wong, 2013; Liu & Perfetti, 2003; Wang & Maurer, 2017; Zhang et al., 2011; Niermeyer et al., 2018). More recently, the laterality differences were argued to be attributed to differences in visual processing demands (the Visuoperceptual Account, Hsiao & Cottrell, 2009, Hsiao & Lam, 2013; Koyama, Stein, Stoodley, and Hansen, 2014; Liu & Perfetti, 2003; Mo, Yu, Seger, & Mo., 2015; Tan et al., 2000) or phonological mapping rules across languages (the Phonological Mapping Account, McCandliss & Noble, 2003; Maurer & McCandliss, 2007; see also Dietz, Jones, Gareau, Zeffiro, & Eden, 2005), respectively in the literature. These two accounts focus on the two aspects that contrast most starkly between alphabetic scripts and non-alphabetic scripts – visual appearance of words and how words map onto sounds.

On one hand, the Visuoperceptual Account postulates that cross-linguistic differences in OT laterality stem from hemispheric specialization for different types of visual processing. The left hemisphere is, traditionally, a sequence analyzer which processes visual stimuli linearly and locally (i.e., focusing on parts and details). In contrast, the right hemisphere concerns with holistic and global aspects (e.g., orientation, spatial relations within a shape) (Cohen, 1973; Christie et al., 2012; Kosslyn et al., 1993; Clements et al., 2006; Corballis, 2003; Ng et al., 2000; Piazza & Silver, 2017). In lieu of these hemispheric specialties, the reading of alphabetic scripts has a greater left-hemisphere dominance as compared to logographic scripts for two reasons. Firstly, linear processing (LH) is preferentially recruited in the reading of alphabetic scripts in which words are essentially linearly arranged letter sequences. Conversely, in logographic scripts such as Chinese, single characters are made of strokes packed within a roughly square shape. The relative positions of strokes within the character determine its meaning. Reading of logographic scripts is thus more reliant on structural and configural processing (RH) than alphabetic scripts (e.g., Liu & Perfetti, 2003; Mo, Yu, Seger, & Mo., 2015; Tan et al., 2000). Secondly, greater detail processing (LH) is required in the reading of alphabetic scripts, as words in the lexicon tend to be more visually similar as compared to logographic scripts (Hsiao & Cottrell, 2009). This is due to the tendency for most alphabetic scripts to have a small number of alphabets (e.g. 26 alphabets in English) that make up a large lexicon (e.g., 170,000 words in English, as listed in the Oxford Dictionary). Thus, words in alphabetic scripts tend to share overlapping letter sequences and have high visual similarity. To successfully distinguish a word from its *lookalikes*, one would need to pay close attention to individual letter identities. In contrast, logographic Chinese has a relatively small lexicon of 10,000 characters (7,000 in general use) made from roughly 600 basic building units called

radicals (as listed in the Chinese Radical Position Frequency Dictionary). As there is far lower visual similarity among Chinese characters comparing to that of alphabetic scripts, the need to pay attention to fine details is reduced during character / word identification.

On the other hand, the Phonology Mapping Account posits that the occipitotemporal laterality for reading is influenced by high-level language processes. According to the Phonological Mapping Hypothesis (McCandliss & Noble, 2003; Maurer & McCandliss, 2007), the left-lateralized activation in the OT region is driven by its communication with the left hemisphere speech comprehension sites in the temporal lobe. Specifically, the left OT is assumed to partake in integrating visual letters (graphemes) with their auditory counterparts (phonemes). This account thus predicts that left-lateralized effects in visual word processing would be more salient in alphabetic scripts, which typically have strong letter-to-sound correspondences. In logographic scripts, however, where character-to-sound mappings are largely arbitrary, there is less of a demand for such a visual-auditory integration process, thereby resulting in less left-lateralized OT activities.

In short, visual word processing engages the occipitotemporal region with typically greater left-lateralized topography for alphabetic scripts compared to logographic scripts. Differences in OT lateralization have been attributed to varying visual processing and phonological demands across scripts. Importantly, the Visuo-perceptual Account adopts a more domain-general perspective which emphasizes pre-existing hemispheric biases and general visual processing mechanisms. On the other

hand, the Phonological Mapping Account assumes that left-lateralization of the OT is induced by communication with left-lateralized high-level language regions. At present, it remains highly debated if occipitotemporal activity and laterality for reading are shaped by domain-general or domain-specific processing demands, or both. A major challenge to resolving this debate is that reading is a complex process that involves many sub-processes, some of which may be domain-general and inter-related in nature. The inconsistent findings in the literature thus could be mainly attributed to the adoption of different experimental designs that highlight different sub-processes in reading through the use of different tasks (i.e. reading task [greater language processing] vs. perceptual judgement [greater visuospatial processing]) and type of control stimuli (i.e. geometric shapes [does not control for low-level visual features] vs. letter-like stimuli [controls for low-level visual features]). Further systematic investigations are warranted to conclude on the specific roles of the bilateral occipitotemporal regions in reading.

The thesis is thus motivated by the research gap to understand the underlying neural mechanism that supports reading. Contributing to the domain-general vs. domain specific debate, Study One explored how OT laterality may be shaped by spatial configuration (general visual processing), and phonological mapping (language-related processing) via an artificial orthography learning paradigm. One major challenge in this field of study is the difficulty in disentangling confounding variables in real-world languages. For example, it is almost impossible to isolate the effects of spatial configuration on OT lateralization as languages that differ in spatial configuration (most often logographic vs. alphabetic scripts) also tend to differ in phonological mapping. Due to the limitations posed by real-world scripts, there has been an increase in the number of studies featuring artificial scripts in recent years (e.g., Brem et al., 2018;

Hirshorn, Wrencher, Durisko, Moore, & Fiez, 2016; Mei et al., 2015; Maurer, Blau, Yoncheva, & McCandliss, 2010). This thesis adds on to this growing body of research by training four groups of subjects to read artificial scripts that differed systematically in spatial configuration and phonological mapping and comparing their OT laterality. Through this approach, conclusions can be made regarding the primary motivator of OT laterality in visual word processing – if it is visuoperceptual or phonological processing demands or both.

The second research focus of this thesis centers specifically on the functional significance of the N170 ERP component in visual word processing. The N170 literature has been highly inconsistent in the reporting of cross-linguistic laterality differences, as well as amplitude differences among words, pseudowords, and consonant strings within the same script. Although a larger number of N170 studies concurred with the fMRI literature in finding bilateral or right-lateralized N170 activity for logographic scripts (Chen, Bukach, & Wong, 2013; Liu & Perfetti, 2003; Wang & Maurer, 2017; Zhang et al., 2011; Niermeyer et al., 2018), reports of left-lateralized N170 activity for logographic reading are not uncommon (Lin et al., 2011; Qin, Maurits, & Maassen, 2016; Wong et al., 2005; Maurer, Zevin, & McCandliss, 2008). Similarly, among studies that compared N170 activation for words, pseudowords, and consonant strings within the same script, some reported enhanced N170 activation for pseudowords than for words, but others failed to observe a difference, or even reported the reverse (reviewed in Maurer & McCandliss, 2008). Due to these mixed findings, it remains inconclusive what the N170 amplitude and lateralization reflect in visual word processing. To uncover the underlying cognitive process(es) indexed by the N170 component, Study Two explored the effects of spatial configuration, stimulus familiarity, and lexicality on

N170 activation and laterality. To further probe the relationship between cognitive processes and neural activity, correlation analyses between cognitive abilities (specifically visuospatial skills and phonological awareness) and N170 activity were performed. Additional analyses on two other early ERP components (P100 and P200) were included to highlight the effects that were unique to each component/time window (with a particular focus on the N170 component).

Taken together, the two studies in this thesis aimed to advance our understanding of the bilateral occipitotemporal region's role in reading through examining how different characteristics of visual words may shape N170 activation and lateralization.

Chapter 2:

Literature Review

2.1 Introduction to The Word N170

The N170 (also referred to as the visual N1) is a negative voltage deflection that peaks approximately 170 ms post visual stimulus presentation (Bentin et al., 1999), observed maximally at occipitotemporal electrode sites (see, for example, Rossion, Joyce, Cottrell, & Tarr, 2003). Two main characteristics of the N170 are that it is reflective of 1) visual expertise, in the sense that its amplitude is larger for familiar than for unfamiliar stimuli (e.g., larger when bird-experts were looking at birds (Tanaka & Curran, 2001) and when car-experts were looking at cars (Gauthier, Curran, Curby, & Collins, 2003)), and 2) automaticity of visual recognition process, such that it is elicited even when subjects are not explicitly instructed to pay attention to the identity of the stimulus (e.g., in a colour detection task: Maurer et al., 2011; and in a word orientation judgment task: Rossion, Joyce, Cottrell, & Tarr, 2003). The N170 is elicited for various kinds of visual stimuli, with the Face N170 (e.g., Bentin et al., 1996) being the most well-established in the literature. However, while face and object recognition typically elicit bilateral or right-lateralized N170 activity, visual word recognition was found to tend towards left-lateralization in literate individuals (Rossion et al., 2003), albeit with less convergence in the literature.

One of the first event-related potential (ERP) studies designed to primarily examine early visual word recognition processes was performed by Bentin and

colleagues (1999), in which words were found to elicit a sharp negative peak at 170 ms at occipitotemporal electrode sites. The mean N170 amplitudes for words (real words), pseudowords (non-meaningful, orthographically/phonologically legal), and nonwords (non-meaningful, orthographically/phonologically illegal) were significantly more left-lateralized than the N170 amplitudes elicited for alphanumeric symbols and geometric forms, an effect later termed as coarse print tuning (although in the literature, coarse N1 print tuning has also been used to refer to general non-lateralized larger amplitudes for letter strings than for symbols). In contrast, N170 amplitudes within orthographic stimuli (word, pseudowords, nonwords) did not differ among themselves, suggesting a lack of fine print tuning at this stage. The distinction in lateralization pattern between orthographic and non-orthographic stimuli was driven by larger N170 amplitudes for orthographic stimuli relative to non-orthographic stimuli in the LH, and numerically larger (not statistically significant) N170 amplitudes for non-orthographic stimuli in the RH. As the left-lateralized response to orthographic stimuli did not further distinguish between legal and illegal word forms, it was concluded that it reflects general visuoperceptual expertise for letters, and not higher-order linguistic processes e.g., phonological or semantic. This was concurred by a subsequent study contrasting N170 lateralization for words, faces, and objects, where the strong left-lateralization observed for printed words as compared to objects and faces was attributed to “aspects of pattern recognition” (Rossion et al., 2003, p. 1619), rather than linguistic processes as the task had minimal linguistic demands. For single letter reading, coarse print tuning effects have been largely inconsistent, with some finding little difference in N170 amplitudes between single letters and symbols (Gros, Doyon, Rioual, & Celsis, 2002; Brem et al. 2018), others finding a bilateral increase in N170 amplitudes (Wong, Gauthier, Woroch, DeBuse, & Curran, 2005; Stevens, MCIlraith, Rusk, Niermeyer, Waller, 2012).

This section briefly introduced the N170, particularly in visual word processing. It was highlighted that the N170 for visual words is generally left-lateralized, while it is bilateral or right-lateralized for faces and objects. Is this functional distinction a consequence of nature or nurture? Is reading experience compulsory for left-lateralization to occur? In the following section, the conditions under which the left-lateralization of the word N170 emerges will be reviewed.

2.2 Emergence of a Left-Lateralized Word N170

As a component that indexes visual expertise, the word N170 was found to develop with increased exposure to letters. Maurer, Brem, Bucher, and Brandeis (2005) found that 6-year-old children who have not received formal reading instruction displayed marginal increased N170 activity for letter strings than for symbols, and this effect was only present in children with high letter knowledge. This initial expertise effect was, however, manifested in the right hemisphere. In a later study by the same researchers, the same group of children who had been receiving formal reading instruction for 1.5 years exhibited strong coarse print tuning effects bilaterally, with reading scores correlating with the degree of tuning in both hemispheres. In a recent presentation by van Setten, Martinez-Ferreiro, Maurits, and Maassen (2018), preliminary findings showed that 12-year-old normal Dutch readers exhibit right-lateralized N170 for words. Bilateral coarse N1 tuning effects were also seen in young Chinese readers (7.7 years old), but in older children (9.4 years old) the effect was left-lateralized, although overall the N170 topography for real characters was bilateral (Tong et al., 2016). The bilateral or even right-lateralized N170 responses in children up to 12 years old contrast with the typical left-lateralized topography in adult readers, and it is

unclear from the literature at which point in the reading development trajectory the left-lateralized N170 emerges. In this respect, the link between the left-lateralization for words and amount of exposure or expertise seems to be not well-established, and the emergence of left-lateralization for words may be partly linked to higher cognitive processes, or maturational factors, rather than visual expertise *per se*.

Evidence of influence from maturational factors comes from functionally illiterate adults who have difficulty reading simple words and sentences. These subjects showed increased left-lateralized N170 for words and pseudowords than for symbols, despite having greater difficulty detecting repetitions in orthographic stimuli than normal readers (Boltzmann & Rüsseler, 2013), demonstrating that the left-lateralization for words may not be strongly associated with reading expertise. With that said, the same study found that literacy training can enhance print tuning effects, and result in greater left-lateralization for orthographic stimuli relative to symbols, indicating that while the onset of left-lateralized N170 for words may not be strictly related to reading level, improving reading skills can induce greater left-lateralization effects. This was contradicted by a later study which found non-lateralized N170 responses in adults who only received formal literacy training in adulthood (Sánchez-Vincitore, Avery, & Froud, 2018). The adult readers in the two studies mentioned differed in factors contributing to illiteracy, such that those in the first study were functionally illiterate due to poor reading ability but subjects in the latter study lacked reading ability due to socioeconomic reasons which disrupted formal literacy instruction in childhood. In sum, developmental and adult literacy studies together show that print tuning effects in young readers are manifested bilaterally. Left-lateralized effects seem to emerge later, with no clear-cut relation to reading expertise, albeit only in adults who have received early reading

instruction which may be indicative of critical/sensitive period effects. The *degree* of left-lateralization in poor readers, however, appears to be enhanced by increased reading ability.

To accurately test if left-lateralized N170 effects can index the increase in reading expertise, training studies on adults with normal reading abilities have been employed to investigate if such effects can emerge after relatively short exposure to new word forms. One of the pioneer adult training study by McCandliss, Posner, and Givon (1997) trained a group of young adults to read Keki, a miniature artificial language consisting of 68 words, over 50 hours of training, spanned over five weeks. The Keki language was made of Roman alphabets but differed from English in some aspects of orthography. Words in Keki language always ended in vowel and contained letter combinations that were uncommon in English. ERP recordings were made prior to training, after 20 hours of training, and at the end of the 50-hour training. N170 amplitudes were the most negative for consonant strings, followed by Keki words, and were the least negative for English words. Retrospectively, this pattern of N170 activations seems to contradict a line of studies that follow, which found that N170 responses for words are larger than or equal to consonant strings. That aside, the main finding of this study was that there were no significant training effects, such that the pattern of N170 responses across stimulus types did not change with training. Furthermore, the N170 for trained and untrained Keki words did not differ after training. Based on these results, it was concluded that the N170 reflects orthographic processing and the magnitude of negativity is associated with the extent of orthographic irregularity, and the emergence of expertise for new word forms that adhere to different orthographic rules likely takes place over an extended period of time.

However, later training studies using both natural and artificial words converged to reach a different conclusion that expertise for a novel script can emerge rapidly, with the shortest training period of merely 20 minutes (Maurer, Blau, Yoncheva, and McCandliss, 2010). In Maurer and colleagues' study, subjects were trained to read 16 artificial words that were visually distinct from Roman letters. After a short training phase of 20 minutes, there was a bilateral increase in N170 amplitudes, with a greater increase in the right hemisphere. This training-related effect was also observed in untrained stimuli in the artificial orthography, suggesting that the right-lateralized increase in N170 reflects general script familiarity, rather than recognition at a lexical level. Bilateral increase in N170 amplitudes was also observed for German readers who were trained to make word-sound associations with Japanese/Chinese characters in a single-session study (Brem et al., 2018). The bilateral or right-lateralized N170 familiarity effects in adults echo with the developmental studies mentioned earlier, where bilateral or right-lateralized word N170 were observed in young readers whose expertise for letters may still be developing. It was thus concluded that initial familiarity effects are characterized by a right-lateralized increase in N170 amplitudes, and a left-lateralized N170 indexes a higher level of expertise, which may not be attainable after merely 20 minutes of training. A later follow-up study using the same artificial orthography stimuli found that after two days of training (the exact number of hours of training was not mentioned), left-lateralized N170 emerged but only in the group which learned the orthographically transparent version via a training paradigm that highlights grapheme-phoneme mappings. In the other group which learned the same artificial words as an orthographically opaque script via different training procedures, the N170 was right-lateralized (Yoncheva, Blau, Maurer, and McCandliss, 2010; Yoncheva, Wise, & McCandliss, 2015). The differences in lateralization patterns between the two

subject groups suggest that the emergence of a left-lateralization N170 for a novel script can be modulated by phonological processing demands. This will be explored in detail in later sections of the literature review.

Taken collectively, learning of a novel script both as a child and as an adult result in greater N170 amplitudes for the newly learnt script, likely a reflection of increased familiarity. The absence of training-related N170 increase in the Keki study was likely attributed to the use of familiar Roman alphabets, which does not constitute learning of a novel script. Importantly, while left-lateralized N170 to orthographic stimuli is commonly elicited in adults reading a native script, initial print tuning effects towards a novel script tend to be bilateral or right-lateralized in both children and adults. For novel script learning, left-lateralized N170 effects have been observed when adults learnt a transparent orthography accompanied with a grapheme-phoneme mapping training focus. The same script, when learnt as an opaque orthography, elicited a right-lateralized N170 response.

In sum, studies reviewed in this section showed that left-lateralized effects in visual word processing emerges relatively late, and may be influenced by factors other than familiarity or reading expertise, such as orthographic transparency and/or method of instruction. This section has thus addressed the “When” aspect of the word N170 left-lateralization effects. The following section will be exploring the “Where” aspect, looking into the purported neuroanatomical correlate of the word N170 – the Visual Word Form Area.

2.3 Neuroanatomical Source of Word N170 – Visual Word Form Area

N170 print tuning effects have been source-localized to an area within the left occipitotemporal region termed Visual Word Form Area (VWFA), commonly accepted to be involved in orthographic processing (Bentin et al., 1999; Provobio & Zani, 2003). The VWFA was first proposed by Cohen and colleagues in 2002, where their neuroimaging experiments found an area within the left midfusiform region ($x = -43$, $y = -54$, $z = -12$; $t = 3.42$) that responded more to written words than consonant letter strings (Cohen et al., 2002). Since then, the VWFA's involvement in reading has been demonstrated reproducibly across different scripts and cultures (Cohen et al., 2002; McCandliss, Cohen & Dehaene, 2003; Bolger, Perfetti, and Schneider, 2005; and Baker et al., 2007; see Dehaene and Cohen, 2011 for a detailed discussion). Different lines of evidence have converged to show that activity in the VWFA critically contributes to reading. For example, lesions within or nearby the VWFA typically result in reading-related deficits, such as pure alexia (Cohen et al., 2003). The reading abilities of both typically developing and reading-impaired children positively correlate with VWFA activations (Shaywitz et al., 2002). Notably, the right homologue of the VWFA and nearby regions exhibit reduced activation for reading tasks over the course of reading development (Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003) as well as reading skill improvement (Shaywitz et al., 2002). Taken together, fluent reading is associated greater involvement of the left occipitotemporal region and reduced recruitment of its right homologue. However, there is much disagreement with regards to the notion that the VWFA is specifically, or even primarily, dedicated to reading.

Logically speaking, it seems unlikely that there should be neuron clusters dedicated solely to reading, since it is a fairly new cultural invention that is hardly universal. Acknowledging this, proponents of a reading-specific VWFA proposed the neuronal recycling hypothesis (Dehaene, 2005), citing the unique ability of humans to take advantage of preexisting brain infrastructure and refine the functions of neuron clusters through learning to account for the apparent neuronal specialization for print. This is also described in the perceptual expertise account (McCandliss, Cohen, & Dehaene, 2003), which proposes that extensive visual experience with a specific stimuli class, i.e., letters in this case, drives the reorganization of neuronal functions, such that a group of neurons becomes increasingly specialized for print as reading experience progress. In a recent longitudinal fMRI study tracking the changes in functional organization of the occipitotemporal region in 6-year-olds during the first year of schooling, it was found that voxels specific to written words were not detected prior to schooling, but rapidly emerged in the left OT within the first 2 to 4 months, accompanied with an acute improvement in phonological mapping skills and reading speed (Dehaene-Lambertz, Monzalvo, & Dehaene, 2018). Retrospective analyses revealed that these voxels were not strongly activated for any stimulus category and had weak specialization to tools prior to reading instruction. These voxels remained weakly specialized for tools, with an additional stronger activation for print after reading instruction. In other words, written words become strongly represented at neuron clusters which are weakly specialized for other stimulus categories, with the weaker specialization unchanged by the development of reading expertise.

The next question that naturally follows is why specifically neuronal clusters from the left occipitotemporal region, and not other regions, are “recycled” for reading.

It has been speculated that the left occipitotemporal region becomes specialized for reading due to its anatomical proximity to left hemisphere perisylvian language areas devoted to spoken language processing. This claim is supported by a lateralization study which found that the lateralization of the occipitotemporal region in visual word processing is the same as the lateralization of the more anterior language production brain regions. (Cai, Lavidor, Brysbaert, Paulignan, & Nazir, 2008). Therefore, for majority of the population with a left-hemisphere dominance for language, the VWFA resides in the left OT. Later studies utilizing high-resolution diffusion weighted data and Resting State Functional Connectivity (RSFC) analyses found that the VWFA, compared to its right homologue, had higher connectivity to left-hemisphere language areas, such as the perisylvian superior temporal, anterior temporal, and inferior frontal areas (Bouhali et al., 2014; Abboud, Maidenbaum, Dehaene, & Amedi, 2015; Stevens, Kravitz, Peng, Tessler, & Martin, 2017).

Other than anatomical proximity and preferential connectivity to left hemisphere language processing regions, existing perceptual biases of the left occipitotemporal region have also been cited as a reason for it to be the prime candidate for a visual word processing hub. The left OT has greater preference for stimulus in the fovea relative to the periphery (Hasson, Levy, Behrmann, Hendler, & Malach, 2002), is involved in analytical rather than configural processing (Ventura et al., 2013), demonstrates sensitivity to line junctions (Szwed et al., 2011), and exhibits perceptual invariance (Lerner, Hendler, Ben-Bashat, Harel, & Malach, 2001). These properties arguably allow for the efficient identification and discrimination of letters, which are constructed with combinations of line junctions. These perceptual biases make the VWFA well suited to be an orthographic store that holds pre-lexical representation of words, i.e. letter

combinations (e.g., bigrams). Its preferential activity for orthographically regular letter strings over consonant strings has been cited as evidence for such a storage system. However, it is unclear why these seemingly domain-general visual processing characteristics would result in stimulus-specific activation of the VWFA. This leads to the other side of the argument, which purports that the VWFA is not specific for visual words.

There is a considerable amount of literature against the specificity of the VWFA for word processing that cannot be overlooked. Following the proposal of the VWFA in 2002, its specificity for written words was immediately challenged with the finding that it is also activated for a variety of other tasks such as naming colours and pictures (Price & Devlin, 2003). Since then, multiple studies have shown the VWFA is also activated for the processing of non-wordlike visual stimuli, such as pictures (Price & Devlin 2003; Ben-Shachar, Dougherty, Deutsch, & Wandell, 2007; Ploran et al. 2007; Starrfelt & Gerlach 2007; Kherif, Josse, & Price, 2011; Van Doren et al. 2010), faces (Mei et al. 2010), as well as false fonts (Xue, Chen, Jin, & Dong, 2006; Xue & Poldrack 2007). Furthermore, although lesions in the VWFA can sometimes result in reading deficits such as alexia (Dejerine, 1892; Cohen et al. 2003; Gaillard et al. 2006), such lesions may not produce alexia exclusively (Behrmann, Black, and Bub, 1990; Behrmann, Nelson, & Sekuler, 1998; Farah & Wallace, 1991; Price & Devlin, 2003) and may instead result in a more general deficit in the simultaneous processing of visual stimuli or the processing of visually complex stimuli (Starrfelt, Habekost, & Leff, 2009). In a study comparing fMRI activity during a visual matching task across words, pseudowords, nonwords, foreign and unfamiliar character strings, and line drawn pictures, Vogel, Petersen, and Schlaggar (2012) found that instead of a specificity or

dominance for word-like stimuli, the left OT had the greatest activity towards foreign unfamiliar characters and line drawings. Follow-up analyses in the same study found that the activity at left OT seems to be driven by visual complexity and phonological grain size of the visual stimuli, such that it was higher for stimuli with more strokes, and for unfamiliar and/or unpronounceable character strings which require character by character processing. In terms of connectivity to other brain regions, the VWFA has also been found to be preferentially connected to brain regions non-specific for language processing. Notably, Vogel, Miezin, Petersen, and Schlaggar (2011) found very weak to weak correlations between the VWFA and other reading-related regions, such as the left inferior frontal gyrus (IFG) and the supramarginal gyrus (SMG). Instead, the VWFA had strongest correlations with regions of the dorsal attention network, with the strength of correlation increasing as age and reading ability increased. The authors thus suggested that the VWFA may not be directly related to reading as previously hypothesized, and may be involved in reading through its role in directing visual attention. It was thus recommended that future work to shift from describing the specific stimulus class (e.g., letters or words) that activates the VWFA, to defining the processing characteristics (e.g., responses to visual complexity and sequenced versus grouped processing) of the VWFA.

In sum, while its functional specificity is highly debated, the involvement of VWFA in reading is undisputed. With formal reading instruction, activity of the VWFA to words increase, and activity of the right homologue region decreases, generating a left-lateralized pattern of activation, complementing left-lateralized N170 effects elicited in visual word processing. However, the functional specificity of the VWFA has important implications for the interpretation of such lateralization effects. On one hand,

a reading-specific VWFA implicates linguistic processing factors in shaping VWFA activity. On the other hand, a domain-general VWFA would attribute VWFA activity to visual processing factors. Accordingly, visuoperceptual expertise for letters as indicated by the magnitude and lateralization of word N170 may also be attributed to different factors, depending on one's view on VWFA specificity. The next section returns to the N170 literature, and reviews how the N170 left-lateralization for visual words has been explained in the field.

2.4 Explaining the Left-Lateralization of Word N170

The observations that words elicit a left-lateralized N170, in contrast to right-lateralized or bilateral activity for faces and objects, accompanied with cross-linguistic differences in lateralization patterns have inspired a wealth of studies probing the underlying factors influencing the lateralization of this ERP component. Theories that attempt to account for the N170 lateralization difference between words and faces/objects fall broadly into two camps, with one emphasizing linguistic influences and the other citing differences in visual attributes. Within the linguistic account, the development of expertise for letters in the left occipitotemporal region has been attributed to 1) its selectivity to orthographic features and visual word forms (Cohen et al., 2003), as reviewed earlier and 2) its involvement in mapping orthography to phonology, given that phonological processing is left-lateralized (Maurer & McCandliss, 2007).

2.4.1 The Phonological Mapping Account

One well-cited theory that emphasizes the role of phonology in the development of the N170 specialization for words is the Phonological Mapping Hypothesis (reviewed

in Maurer & McCandliss, 2008). According to the Phonological Mapping Hypothesis, left hemisphere specialization for print reflects automatic connections between pre-existing left hemisphere regions associated with phonological processing, and occipitotemporal regions related to visual word processing. In other words, the left occipitotemporal cortex becomes increasingly specialized for print as beginner readers learn to associate orthography with phonology.

In support of this hypothesis, a line of developmental studies has demonstrated as children receive reading instruction, their N170 towards print change from bilateralized to increasingly left-lateralized. For example, in a series of longitudinal studies conducted by Maurer and colleagues, children who carried out a visual one-back task with blocks of words and symbols demonstrated no clear N170 amplitude differences between words and symbols in preliterate children (Maurer, Brem, et al., 2005), and larger N170 amplitudes for words than for symbols in second graders (Maurer et al., 2006), with this difference still significant but smaller when the children reached fifth grade (Maurer et al., 2011). The reduction of N170 specialization in expert readers is suggested to be reflective of acquired efficiency, as reading becomes more automatic and require less attention to the appearance of the letters, and/or the phoneme conversion rules. In a similar vein, albeit with less consistency in the findings, neoliterate adults also tend to exhibit more left-lateralized N170 after reading training, in contrast with a bilateralized response at pre-training. Studies employing artificial orthography training have also been successful in inducing a more left-lateralized response for the trained artificial words as compared to untrained symbols.

Support for the phonological mapping hypothesis also comes from a stream of dyslexic research, demonstrating that dyslexic readers, with a core deficit that is phonological in nature, typically have delayed and weakened N1 print tuning. In two longitudinal studies conducted with dyslexic and age-matched control children, dyslexic children showed signs of N170 specialization to print in the fifth grade, while the control children exhibited print tuning in the second grade, soon after the onset of formal reading instruction (Maurer et al., 2011). Dyslexic children elicit similar N170 amplitudes when viewing words and symbol strings, and this lack of specialization towards print continues to persist in pre-adolescence (Araújo, Bramão, Faísca, Petersson, & Reis, 2012) and adulthood (Mahé, Bonnefond, Gavens, Dufour, & Doignon-Camus, 2012). Importantly, a study found that poor readers, who had low reading abilities due to low socio-economic status and poor reading habits, had similar N170 tuning to control typical readers, even though their reading levels were matched with that of dyslexic readers who did not demonstrate N170 tuning for print (Mahé, Bonnefond, & Doignon-Camus, 2013). Therefore, the weak N170 print specialization in dyslexic readers is primarily attributed to poor phonological skills, rather than reading skills in general.

Indeed, many studies in the literature have established a close relationship between N170 tuning and one's phonological skills, rather than general reading ability *per se*. In typically developing children, individual phonological awareness, but not vocabulary size or age, predicted the degree of N170 tuning to words versus stimuli that were not word-like (Sacchi & Laszlo, 2016). In dyslexic children, initial N170 amplitudes to words prior to a letter-speech sound correspondence training program predicted the extent of improvement in reading skills, such that improvers showed larger

N170 amplitudes to words compared to non-improvers at pre-training (Fraga González et al., 2016). This suggests that N170 amplitudes to words may qualify as a neural predictor of how sensitive one is to an intervention program that targets phonological processing. Conversely, short (5 weeks) phonics training (i.e. learning letter-to-sound correspondences and practicing sound blending) was found to enhance N170 amplitudes to trained words, as demonstrated in a case study on a 13-year-old Japanese girl with severe learning difficulty in English (Okumura, Kita, & Inagaki, 2017).

2.4.2 The Visuoperceptual Account

In the earlier section on VWFA, the Visuoperceptual Account was briefly introduced to be the proponents of a domain-general VWFA. It explains the left-lateralization of visual word processing with hemispheric biases for visuoperceptual processes, such as the left occipitotemporal region's sensitivity to visual complexity and stimulus graspability. Traditionally, the left hemisphere is a sequence analyzer which processes visual stimuli linearly and locally (i.e., focusing on parts and details). In contrast, the right hemisphere concerns with holistic and global aspects (e.g., orientation, spatial relations within a shape) (Cohen, 1973; Christie et al., 2012; Kosslyn et al., 1993; Smith et al., 1995; Clements et al., 2006; Corballis, 2003; Ng et al., 2000; Piazza & Silver, 2017). Intriguingly, the left-lateralized N170 for words was found to be diminished when presentation times were brief (30 ms) (Mercure, Dick, Halit, Kaufman, & Johnson, 2008). Shortened presentation times may have greatly increased demand on visuospatial analysis, and at the same time may impede detail processing. Thus, the bilateralized N170 at short presentation times may reflect increased effort in

visuospatial analysis, or engagement of global processing which is shown to be right-lateralized, or a combination of both effects (Moses et al., 2002; Hellige, 1996).

Another visuoperceptually-grounded explanation for the left-lateralization of the word N170 makes references to the hemispheric biases for different spatial frequencies. The left hemisphere is evolutionarily specialized to process abrupt spatial changes such as sharp edges and fine details, referred to as high spatial frequency (HSF) visual information, in contrast to low spatial frequency (LSF) visual information, which reflects coarse changes over large distances. In a divided visual field paradigm where subjects were showed pictures that consisted of the full spectrum of spatial frequencies or were spatially filtered, Peyrin et al. (2003) found hemispheric advantages for different ranges of spatial frequencies. When subjects were shown pictures composed of the full spectrum of spatial frequencies, no hemispheric dominance was observed. However, when the pictures were filtered to conserve only HSF, a right visual field (RVF/LH) advantage was demonstrated. Conversely, when the pictures were filtered to retain only LSF, a left visual field (LVF/RH) advantage emerged.

In yet another study adopting a divided-visual field paradigm, Kitterle, Christman, and Hellige (1990) found that subjects were faster at identifying gratings of high spatial frequency (6 – 9 cycles per degree) in the right visual field (RVF/LH) and faster at identifying gratings of low spatial frequency (0.5 – 2 cycles per degree) in the left visual field (LVF/RH). Critically, previous studies show that the reliable identification of letters occur at a high spatial frequency of 1–3 cycles per letter (CPL) (e.g., Wang & Legge, 2018). Notably, Mercure, Dick, Halit, Kaufman, & Johnson

(2008) found that the N170 left-lateralization for words was significantly attenuated when the stimuli were lowpass-filtered, suggesting that the commonly observed left-lateralization may be at least partly attributed to high spatial frequency information which support word recognition. Hence, it seems that the left hemisphere, with a hemispheric bias for high frequency information, is inherently more suited for visual word processing.

Also originating from a visuoperceptual perspective, Hsiao and Cottrell (2009) asked if the left-lateralization commonly observed in alphabetic scripts could be dependent on visual characteristics such as spatial frequency information, independent of the LH's assumed role in language processing. Utilizing computational modeling, it was found that in scripts with a small alphabet size, words in the lexicon tend to have high visual similarity. More analysis of high spatial frequency information is thus required to distinguish words, placing greater demands on the left hemisphere. Accordingly, the left-lateralization effects observed in alphabetic scripts may be attributed to a relatively small pool of building blocks (e.g., 26 alphabets in English). The same study also found that languages that feature grapheme-phoneme conversion require more HSF/LH processing as well. However, in contrast to the Phonological Mapping Hypothesis which attributes this LH dominance to connections to LH phonological processing areas, here the LH lateralization is argued to be attributed to the requirement to decompose a word into graphemes, which emphasizes the identity of individual letters, thus requiring attention to HSF information and taxing on the left hemisphere.

2.4.3 Phonological Mapping vs Visuoperceptual Accounts

Towards the end of the preceding paragraph, some sort of language-dependent lateralization effects were hinted at, with the finding that scripts with small alphabet size and consistent grapheme-phoneme mapping would engage the left hemisphere to a larger degree. Naturally, the Phonological Mapping Account and the Visuoperceptual make slightly different predictions with regards to how different orthographic properties may motivate lateralization, since they were formulated based on different assumptions. Under the Phonological Mapping Hypothesis, languages that utilizes grapheme-phoneme conversion rules should elicit greater left-lateralization, since left-lateralization is theorized to stem from extensive coupling of orthographic and phonological processes. On the other hand, the Visuoperceptual Account predicts that the extent of left-lateralization is modulated by the nature and amount of visuospatial analysis, such that scripts that are more visually complex, with lower visual similarity in the lexicon, and those with their phonologies accessed mainly via whole-word mapping (i.e., lack of consistent grapheme-phoneme conversion rules) would be less left-lateralized. Therefore, both accounts make the same prediction that languages with higher orthographic transparency would elicit more left-lateralized N170 than languages that are more orthographically opaque, albeit from different perspectives. The Visuoperceptual Account makes an additional prediction that orthographies that differ in general visuospatial features would also elicit different lateralization patterns. In the following section, we will review the literature on OT laterality differences in languages with different orthographic mapping principles, and distinct visual appearances.

2.5 Cross-Linguistic Differences in Word N170 Lateralization

Neuroimaging evidence has converged to show divergence in the lateralization patterns of the occipitotemporal region for logographic languages (typically Chinese or Japanese Kanji) and alphabetic languages (most often English). This difference in lateralization is mainly driven by a greater involvement of the right occipitotemporal region in the reading of logographic characters. This was concluded in multiple meta-analyses of neuroimaging studies on reading in different language systems (Bolger, Perfetti, & Schneider, 2005; Tan, Laird, Li, & Fox, 2005), which unanimously found a significant right occipitotemporal activation for logographic scripts, and a clear left-lateralized occipitotemporal activation for alphabetic scripts. The greater involvement of right hemisphere occipitotemporal region led to reports of bilateral (e.g., Nelson, Liu, Fiez, & Perfetti, 2009; Liu, Dunlap, Fiez, & Perfetti, 2007; Tan, Feng, Fox, & Gao, 2001) or even right-lateralized (Tan et al., 2000) activity in the region, although some observed left-lateralized activation (e.g., Kuo et al., 2001).

Although the additional engagement of the right occipitotemporal region in logographic reading is well supported by numerous meta-analyses of fMRI studies, the N170 literature is considerably less consistent. While some studies found that the reading of logographic scripts elicit bilateral N170 activity (Chinese: Chen, Bukach, & Wong, 2013; Liu and Perfetti, 2003; Wang & Maurer, 2017; Zhang et al., 2011; Japanese: Niermeyer et al., 2018), left-lateralized N170 responses have also been reported (Chinese: Lin et al., 2011; Qin, Maurits, and Maassen, 2016; Wong et al., 2005; Zhao et al., 2012 (marginally left-lateralized); Japanese Kanji: Horie et al., 2012; Maurer, Zevin, & McCandliss, 2008). In contrast, left-lateralized N170 effects is

generally observed in alphabetic scripts such as English (Bentin et al., 1999), French (Mahe et al., 2012), and German (Maurer et al., 2005). The reason for such discrepancies between fMRI and ERP findings is unclear, and it is not the intention of this thesis to delve into the differences between two neuroimaging methods. It remains that some cross-linguistic differences in lateralization do exist regardless of the method of study. The differences in lateralization patterns between languages have been attributed to both linguistic (e.g., orthographic and phonological) and non-linguistic (e.g., visuospatial) processing demands that vary across scripts.

2.5.1 Cross-linguistic Differences in Visuoperceptual Processing Demands

Logographic scripts and alphabetic script can differ vastly in visual appearance. Taking logographic Chinese as an example, the basic perceptual unit for reading and writing in Chinese is a character. A character can be made of basic building blocks referred to as radicals, which are spatially arranged in many possible configurations, all while keeping within a roughly square shape. The visual complexity of Chinese characters increases as the number of strokes within the character increases, as there is a greater amount of visual information confined within a square configuration of a given font size. Given such visual characteristics, the processing of Chinese characters is thought to require more visuospatial analysis compared to alphabetic languages, where words are made of a smaller set of letters, arranged in a linear configuration, and increase in string length as the number of letters increase (Liu et al., 2007; Tan et al., 2000). In a sample of Chinese and Taiwanese young readers, their reading skills were best predicted by their visual skills. In contrast, the same study found that the reading skills of British children were associated with phonological skills (Huang & Hanley, 1997). From the Visuoperceptual perspective, the higher demand on visuospatial

analysis in Chinese reading is a primary reason for the greater recruitment of right hemisphere regions, which are specialized in holistic and spatial processing. On the other hand, the processing of letter strings in alphabetic languages is said to be more reliant on constituent analysis and assembly process, and thus requires the left hemisphere's role as a temporal, sequential analyzer.

Furthermore, there is far greater number of building blocks (541 radicals) in Chinese than in most alphabetic languages (e.g., 26 alphabets in English). This, coupled with the much larger lexicon size in alphabetic languages (170, 000 words in English vs. 7, 000 characters in Chinese), imply that words in alphabetic scripts tend to be more visually similar than words in logographic scripts. The greater visual similarity in alphabetic scripts may thus engage the left hemisphere to a larger extent as more analysis of high spatial frequency and detail information is required for word identification.

2.5.2 Cross-Linguistic Differences in Phonological Processing Demands

Differences between Chinese and alphabetic languages do not end at visual appearance, as they also differ in the mapping of phonology. A script with consistent grapheme-to-phoneme conversion rules is considered a shallow orthography, while a script with little/no correspondence between graphemes and phonemes is considered a deep orthography (Frost & Katz, 1992). Chinese is considered an extremely deep orthography as there is no predictable relationship between graphemes and phonemes (Hoosain, 1991), and visually similar characters often have unrelated pronunciations. Within alphabetic languages, English is considered a relatively deep orthography as there are many instances of one-to-many and many-to-one phoneme-grapheme

mappings. For example, the phoneme /f/ may be represented by the letter “f” or the letters “ph” in English, and the letter “i” is pronounced as /I/ in *tint*, but /aI/ in *pint*. According to the Orthographic Depth Hypothesis, shallower orthographies would require greater amount of phonological recoding to attain lexical access. Therefore, to attain lexical access from visual words, shallow orthographies such as Italian would engage more phonological recoding than English, a relatively deep alphabetic script, which would in turn involve more phonological recoding than Chinese, an opaque logography.

Although English is a relatively deep orthography, a number of studies have demonstrated that for English word identification, lexical access is still attained via phonology primarily. Lukatela and Turvey (1991) investigated the effect of briefly presented word primes on the naming of pseudohomophone targets presented subsequently. A series of semantically related primes and targets (e.g. *table – chair*), pseudohomophones (e.g., *table – chare*) and unassociated pairs (e.g. *novel – chair*) were presented for naming. Facilitation was found when the targets shared phonological characteristics with associates of the primed words. For examples, targets like *chare* (a pseudohomophone of *chair*) were named faster when primed with *table* than when they were primed with unrelated words or non-words. This suggests that phonology plays an important role in lexical access of visually presented English words. Lukatela and Turvey (1994) followed up with another study which investigated the relative contribution of phonological and orthographic components in priming, and found that strong effects were found for the homophone and semi-homophone primes in the identification of associated target words, but not for primes that were orthographically

similar to the target words. This suggests that assembled phonology is the dominant route in English word identification, despite it being a relatively deep orthography.

While there is general agreement on the importance of phonology in reading English, previous studies diverged in concluding if phonology assumes a critical role in Chinese reading. A handful of studies have demonstrated that phonological processes are important for lexical access in Chinese (see Perfetti & Liu, 1995 for a review). However, several studies have also suggested that phonological processes are less critical, or even assume no role, in Chinese word identification (e.g., Tan, Hoosain, & Peng, 1995; Wong & Chen, 1999; Zhou & Marslen-Wilson, 2000). Using a masked priming paradigm in a lexical decision task, Tan, Hoosain, and Peng (1995) demonstrated that graphic structures of Chinese characters, rather than phonological information, played an important role in Chinese word identification. Masks consisted of graphic characters which were visually similar to the target, phonological characters which were homophonic but orthographically dissimilar to the target, semantic characters which were synonymous but orthographically and phonologically unrelated to the target, and unrelated control characters. Graphically similar masks facilitated the target character's identification, but not the phonetic and semantic masks. From the Phonological Mapping perspective, the active role of phonology in word processing in alphabetic scripts such as English, in contrast to its reduced role in Chinese, is the main motivator behind the cross-linguistic N170 lateralization differences. The increased left hemisphere activity in alphabetic visual word processing is thus said to stem from the greater involvement of phonological processing, which is typically left-lateralized.

In sum, cross-linguistic differences in N170 left-lateralization have been primarily attributed to differences in visual appearance and phonological mapping. Unfortunately, disentangling the effects of phonological and visual processing demands can be extremely challenging with the use of naturally-occurring languages as they tend to differ both in visual appearance and orthographic transparency, among other language features. The functional significance of N170 activity and lateralization in visual word processing thus remain to be uncovered.

2.6 Artificial Orthography Training Studies

In recent years, recognizing the limitations of natural language comparisons, researchers started to employ the use of artificial orthographies to investigate isolated effects of phonology mapping on OT lateralization. To study the effects of orthographic transparency on N170 lateralization, Yoncheva, Blau, Maurer, & McCandliss (2010) trained subjects to read an artificial scripts of glyph words with either consistent grapheme-phoneme correspondence or without. To enhance learning performance, each group also underwent different training procedures, such that the former was trained with a grapheme-phoneme mapping focus and the latter was trained with a whole-word focus. After merely two days of training, subjects exhibited different N170 lateralization patterns, such that those trained to read words with consistent GPC rules elicited more left-lateralized activations than those trained in words assessed via whole-word mappings. This effect is later replicated in Yoncheva, Wise, & McCandliss (2015).

Adopting a similar paradigm coupled with fMRI technique for better spatial resolution, Mei et al. (2013) trained subjects to read artificial words made of Korean

Hangul characters either as a transparent or an opaque orthography. Similar to Yoncheva (2010), subjects in the two groups received different types of training, with the transparent orthography group learning the pronunciations of individual letters before assembling the pronunciation of the whole word, while the opaque orthography group was encouraged to learn the pronunciation of whole words via rote memory. Contrasting pre-training and post-training occipitotemporal activity, the authors found that those who were trained in a transparent orthography had significantly more left-lateralized activation compared to those who were trained in an opaque orthography, but this effect was only significant in the posterior occipitotemporal region, away from the more anterior VWFA.

In another study by Moore, Durisko, Perfetti, and Fiez (2014), subjects were trained to read an alphabetic script where the words are constructed with either Korean characters, or with faces, which tends to rely on holistic and low spatial frequency visual analysis processes, and typically elicits right-lateralized or bilateral activation in the occipitotemporal region. Faces were chosen to test the linguistic account against the visuoperceptual account of the VWFA, by asking if any stimuli that gains linguistic value would induce left-lateralized activations in the occipitotemporal region, regardless of the visual spatial processing demands. Subjects completed an extensive training programme spanning over nine days, first learning the identity and sounds of the alphabets before learning words and finally progressing to reading stories in the assigned script. In favour of the linguistic account, both FaceFont and KoreanFont groups elicited training effects characterized by an increase in activation at a location consistent with the VWFA, but not in the right occipitotemporal region. Further support for the linguistic account is seen in the correlation between faster reading times and

greater left OT activation. However, the linguistic account fell short of explaining the full spectrum of findings. The observation that the FaceFont group had less activation within the left OT indicates that visual spatial processing demands play an important role in shaping OT activity in reading. Furthermore, FaceFont group had slow reading times than the KoreanFont despite undergoing identical training programmes, suggesting that faces were not as facilitative towards the reading process as typical letters, possibly due to differences in their visual spatial properties. In addition, the mean locations of training related activity in the left OT were different for the two font groups, with FaceFont group eliciting a peak response near the left homologue of the FFA, while KoreanFont group's peak response was near the prototypical location of the VWFA. This points to the sensitivity of the VWFA to visual spatial information, where letter-like information is preferentially processed in this region relative to low spatial frequency face stimuli, even though both sets of stimuli have been assigned the same linguistic value. All in all, Moore and colleagues demonstrated the how the linguistic account and the visuoperceptual account together capture the properties of the VWFA in an interactive manner.

A later fMRI study by the same group trained subjects to read the face stimuli either as an alphabetic script (FaceFont in the 2014 study) or as an alphasyllabic script, where each face mapped on to a single English syllable (Hirshorn et al., 2016). As with previously mentioned artificial orthography training studies (Yoncheva et al., 2010, 2015; Mei et al., 2013), the two groups underwent different training paradigms to facilitate the learning of different mapping rules. At post-training, while the alphabetic group elicited a left-lateralized response in the occipitotemporal region, the alphasyllabic group elicited a bilateral response, indicating that the mapping grain size

shapes the laterality of the region. Furthermore, within the alphasyllabic group, the extent of bilaterality in OT activity was related to reading speed, such that those with more fluent reading elicited more bilateral responses. This contrasted with the 2014 study where the fluent reading of alphabetic scripts was related to a left-lateralized response in the OT. These findings demonstrate that the engagement of right OT is facilitative towards the reading of orthographies with larger mapping grain sizes, such as syllabaries and logographies, providing support to the Phonological Mapping Account.

In sum, recent artificial orthography training studies converge to show that the laterality of OT activation for reading can be shaped by orthographic transparency and visual spatial processing demands, such that non-transparent orthographies elicit bilateral activation while transparent orthographies produce a left-lateralized one; and that stimulus that encourages relatively more low spatial frequency processing i.e. faces, results in a weaker left-lateralization than typical letter forms, which encourage high spatial frequency processing.

2.7 Summary of the Literature

The N170 is an ERP component that reflects visual expertise, such that it is greater in magnitude for familiar than for unfamiliar visual stimuli. It can be elicited by a wide range of visual stimulus e.g., faces, objects. For visual words, the N170 topography tends to be left-lateralized in adult readers, as opposed to being bilateral or right-lateralized for faces and objects (Mercure, Kadosh, & Johnson, 2011; Rossion, Joyce, Cottrell, & Tarr, 2003). This left-lateralized N170 topography in visual word

processing has been linked to an area within the left occipitotemporal region termed the “Visual Word Form Area” (VWFA) (Brem et al., 2009; Simos et al., 2007). The VWFA is largely accepted to be crucially involved in reading across scripts, although its specific role in reading is still under debate (e.g., Centanni et al., 2017; Dehaene & Cohen, 2011; Price & Devlin, 2011; Vogel et al., 2014; Wimmer & Ludersdorfer, 2018).

A left-lateralized topography of the N170 is generally indicative of expertise in reading (McCandliss, Cohen, & Dehaene, 2003). Left-lateralized N170 for orthographic stimuli emerges when one has gained substantial knowledge about an orthography, and the degree of left-lateralization has a positive relationship with letter knowledge and phonological awareness (Brem et al., 2018; Curziatti, Bonnefond, Staub, Vidailhet, & Doignon-Camus, 2017; Mahé, Bonnefond, Gavens, Dufour, & Doignon-Camus, 2012; Wong, Gauthier, Woroch, Debuse, & Curran, 2005). In naive readers or individuals with reading disorders e.g., dyslexia, the left-lateralized N170 effects are often weakened, or entirely absent, and can result in observations of bilateral or right-lateralized topographies (Kast, Elmer, Jancke, & Meyer, 2010; Mahé et al., 2012; Shaul, Arzouan, & Goldstein, 2012).

However, this relationship between reading expertise and N170 left-lateralization seems to be more salient in alphabetic scripts such as English and German. In logographic scripts such as Chinese and Japanese Kanji, bilateral and right-lateralized N170 topographies have been reported even for adult expert readers. This echoes with the fMRI literature, in which the greater involvement of the right occipitotemporal region in logographic reading was concluded in several meta-analyses. It thus seems that N170 lateralization for visual words may reflect more than just familiarity or

reading expertise. In the literature, the cross-linguistic differences in N170/occipitotemporal laterality have been primarily attributed to different visual processing demands (Visuoperceptual Account), and differences in phonological mapping (Phonological Mapping Account).

The Visuoperceptual Account (e.g., Hsiao & Cheung, 2016; Hsiao & Cottrell, 2009; 2013; Koyama, Stein, Stoodley, and Hansen, 2014; Liu & Perfetti, 2003) posits that the N170 is differentially lateralized for alphabetic and logographic scripts because they engage different types of visual processing. The left hemisphere is biased towards linear, local, and analytical processing, while the right hemisphere concerns more with holistic, global, and configural information. Alphabetic reading is more left-lateralized as it is dependent on a linear and detailed process that emphasizes the analysis of individual constituent units (letters) within words, due to the linear configuration and high visual similarity among words. In contrast, logographic reading is bilateralized or right-lateralized as it requires the analysis of stroke/radical positions within a roughly square shape, thus emphasizing holistic and configural information. On the other hand, the Phonological Mapping Account (McCandliss & Noble, 2003; Maurer & McCandliss, 2007) puts forth the notion that the degree of left-lateralization of a script is determined by the existence of consistent grapheme-phoneme mappings. The rationale of the Phonological Mapping Hypothesis is that the left-lateralization of the N170 is driven by the regular co-activation of posterior visual regions and the left temporal regions for phonological processing. Therefore, left-lateralization is expected to be stronger in alphabetic scripts in which grapheme-phoneme mappings are much more consistent and predictable as compared to logographic scripts.

Due to these conflicting explanations of cross-linguistic N170 laterality differences, recent studies have turned to computational modelling and artificial orthography training paradigms to study the isolated effects of each of the factors (i.e., visual similarity among words, and availability of consistent phoneme-grapheme mappings). Both the Visual Account and the Phonological Mapping Account have received support from studies conducted thus far, which often involved holding one factor constant and manipulating the other (e.g., holding visual appearance constant and varying the consistency of phoneme-grapheme mappings). Critically, a computational modelling study found that a script with greater grapheme-phoneme mapping consistency could engage the left hemisphere more so than an orthographically opaque script simply by virtue of requiring greater detailed visual processing to individual letters (Hsiao & Cheung, 2016). Such a finding suggests that phonological mapping rules of a script may influence N170 lateralization in a different manner than that described in the Phonological Mapping Account, via a primarily visual process. Therefore, the Visual Account predicts that both phonological mapping rules and visual appearance of a script would contribute to its N170 laterality. In contrast, the Phonological Mapping Account only makes predictions with regards to phonological mapping rules. Past studies that found greater N170 left-lateralization for orthographically transparent scripts as opposed to opaque scripts can thus be interpreted to support either account. Evidently, further work is required to verify the predictions of both accounts.

It is noteworthy that the cross-linguistic differences mentioned above have not been consistently reported. The inconsistency mainly stems from reports of left-lateralized N170 activities for logographic scripts, which do not fit well with the predictions of both the Visual Account and the Phonological Mapping Account. On top of that, there are also inconsistencies found in the way the N170 is lateralized for different types of orthographic stimuli within a single script. Other than reflecting general expertise for orthographic stimuli, the lateralization of the N170 has also been suggested to distinguish between well-ordered letter strings versus nonsense strings (words & pseudowords vs. nonwords) and even between meaningful words and non-meaningful pseudowords. Reports of this further distinction within orthographic stimuli (commonly known as fine N1 tuning effects) have been highly inconsistent. While some studies reported the absence of such effects, others reported significant tuning effects but did not converge on the directionality (e.g., some found greater left-lateralization for words than pseudowords, and others the reverse; reviewed in Maurer & McCandliss, 2008). These inconsistencies in results indicate that N170 lateralization effects in visual word processing are generally poorly understood, and further studies are warranted to examine the functional significance of the N170 in visual word processing.

Chapter 3:

Outstanding Issues to be Addressed in the Present Work

Previous studies that utilized artificial orthographies have been successful in isolating the effects of a single orthographic property on OT lateralization. However, these studies fall short in several aspects, resulting in unresolved concerns. First, in nearly all the studies reviewed above (except for Moore and colleagues' 2014 study on KoreanFont and FaceFont), the two experimental groups not only learned orthographies with different mapping principles, but also underwent different training paradigms. In these studies, typically, subjects assigned to learn the transparent orthography received explicit instructions on the associations between graphemes and phonemes before progressing to whole word reading, while subjects learning the non-transparent orthography were trained to learn whole word mappings right from the beginning. Multiple studies have shown that phonics training of varying durations can enhance left OT activation (Shaywitz et al., 2004; Simos et al., 2007), as well as N170 negativity in the LH (Boltzmann & Rüsseler, 2013; Okumura et al., 2017; Spironelli, Penolazzi, Vio, & Angrilli, 2010). Therefore, it is reasonable to hypothesize that the explicit grapheme-phoneme correspondence instruction that emphasizes reading of single letters may result in a heightened left-lateralized response in the OT, compared to natural language acquisition. In other words, what previous studies have reported may be the combined effects of both different mapping principles and different training paradigms. In order to truly isolate the effects of mapping principles, an inherent orthographic property, subjects across different orthographic transparency conditions should undergo identical training paradigms. Differences observed between groups, if any, could then be solely attributed to differences in mapping principles.

Second, other than in Mei et al. (2013), nearly all studies reviewed were mapping an artificial grapheme onto an English grapheme, phoneme or syllable, resulting in real English words. This, as pointed out by Moore and colleagues (2014), may result in subjects associating each artificial grapheme with an English letter, thereby preferentially activating the neural substrates that support English reading, which tends to be left-lateralized in the OT. It may be unrealistic to expect subjects to learn non-native phonemes within a short training schedule, as a large body of literature has shown that the ability to distinguish between non-native phonemes decreases drastically after the first year of age. However, influence from English reading can be minimized by ensuring that the artificial words do not sound like real words in English. It thus remains unclear if left-lateralization effects would still be observed if the artificial words correspond to non-meaningful syllables in English, especially with an active task that places higher demands on linguistic processes e.g. reading verification task.

Third, artificial orthography training studies thus far have primarily investigated effects of phonological mapping while keeping visual appearance constant. How visual appearance of an orthography may independently influence OT lateralization remains poorly studied. As pointed out earlier in the literature review, both the Visuoperceptual Account and the Phonological Mapping Account make the prediction that orthographically transparent scripts would induce greater left OT activity than orthographically opaque scripts, while attributing the effect to different underlying mechanisms. The Visuoperceptual Account makes a further prediction that visual appearances of orthographies would also influence OT laterality. There is thus a critical need for the investigation of how the visual appearance and orthographic transparency of scripts motivate the lateralization of OT activity independently and interactively.

Relatedly, although differences in spatial configuration of Chinese characters and alphabetic strings have been repeatedly named as a major difference between the two scripts, the specific effects of linear vs. square constructions have not been investigated, to the best of my knowledge.

To address the three problems detailed above, the artificial orthography training in Study One of this thesis 1) had subjects across different artificial orthography conditions undergo identical training procedures, 2) featured artificial words which did not resemble real English words, and 3) contrasted linear and square orthography constructions.

Another outstanding issue addressed in this thesis is the inconsistent N170 print tuning effects reported in the literature. There have been discrepancies in the reporting of coarse print tuning effect, such that print tuning effects were absent when the control stimulus was a close visual match (e.g., false fonts, scrambled letters). There are even more disagreements among studies which have examined fine print tuning effects, resulting in a plethora of observations and interpretations. Such inconsistencies indicate that we have yet to fully capture the functional properties of the N170 in visual word processing. This is perhaps related to the divergence in the understanding regarding the VWFA's specific role in reading, given that it is the neuroanatomical source of the left-lateralized N170 effects in visual word processing. At present, researchers still remain divided on whether the VWFA is a general visual area, or an area that is involved specifically in language processes. There are recent works suggesting that different portions of the left occipitotemporal region (encompassing the VWFA) are responsible

for different stages of visual word processing, such that the posterior regions are primarily involved in extracting visual features, and the anterior regions are more heavily involved in integrating information with other language regions (Seghier & Price, 2011; Lerma-Usabiaga, Carreiras, & Paz-Alonso, 2018). However, it remains obscure if the N170 reflects a perceptual stage (Visuoperceptual Account), an integration stage (Phonological Mapping Account), or both. Study Two of this thesis takes the first step in tackling this problem by comparing bilateral N170 activity elicited by various types of visual stimuli that differ in word-likeness, familiarity, and spatial configuration.

Chapter 4:

Study One: The Roles of Orthographic Depth and Spatial Configuration in Shaping N170 Lateralization: An Artificial Orthography Training Study

4.1 Overview

How do visuoperceptual and phonological mapping properties independently and interactively shape the laterality of the N170 component, and in turn what does this tell us about the nature of the N170? In an attempt to address this complex question, Study One examines the effects of spatial configuration (visuoperceptual) and orthographic depth (phonological mapping) on 1) the cognitive correlates of learning success and 2) N170 lateralization.

Considering that the effects of orthographic depth and aspects of visual spatial processing demands have been separately investigated in previous studies, this study makes two novel contributions: 1) this is the first attempt to look into the effects of linearity by contrasting linearly-constructed and squarely-constructed artificial orthographies, and 2) this study is also the first to systematically compare and contrast orthographic transparency and spatial configuration within the same study. This is achieved via an artificial language learning paradigm. As pointed out in the literature review, isolating the effects of a single orthographic feature, such as orthographic depth, is almost impossible when comparisons are made between natural languages, as they often differ in more ways than one. Recent studies have thus called for the use of

artificial orthographies, which would allow us to systematically study the effects of a single orthographic feature on learning behavior and on lateralization patterns. This study features four artificial orthographies that contrast only in orthographic depth and spatial configuration, while all other variables (e.g., pronunciation, letter combination) have been held constant.

Previous artificial orthography training studies commonly controlled for the exposure each subject had to the stimuli by ensuring that each subject received an equal number of trials. However, in this study, subjects were given the liberty to revise the visual-auditory mappings for an unlimited number of times, while keeping within a reasonable time limit (no more than 30 min) for each session. This inevitably resulted in more stimuli exposure for the deep orthography groups as the lack of consistent grapheme-to-phoneme mappings meant that subjects needed more time to learn the words via rote memory. The primary aim of this design was to ensure that participants across different conditions achieve similar accuracy rates towards the end of the training, so that the post-training ERP data would reflect the effects of successful learning. Another notable difference between this study's design and that of previous studies is that no semantic component was involved in this study. In all of the artificial orthography training studies reviewed, word meaning was introduced either explicitly (e.g., via mapping onto a picture), or implicitly, where letter combinations always resulted in a real English word. In an attempt to focus on orthographic processing and reduce the influence of semantic information, most of the artificial words (20 out of 24) featured in this study were not meaningful in English.

While it is clear from the literature that English and Chinese reading have overlapping but distinct cognitive precursors (with English reading more reliant on phonological skills and Chinese reading more dependent on visual spatial processing skills), it remains unknown what specific aspects of the languages motivate such differences. To fill this research gap, this study asks how orthographic transparency and spatial configuration individually and interactively drive the differences in cognitive precursors. To that end, a battery of tests assessing phonological skills and visual spatial processing skills were administered, and scores on these tests were used to correlate with subjects' learning performance in the artificial orthography learning. In addition, a non-verbal IQ test and a working memory test were also administered to verify that there were no significant (artificial orthography) group differences in participants' general cognitive abilities. This ensured that differences (if any) in learning performance between groups could not have arisen from individual differences in general cognitive abilities.

Guided by past studies, it is predicted that the learning of shallow orthographies (LS & SS) will be more reliant on phonological skills, such that subjects with stronger phonological skills will achieve better word learning performance, as indicated by higher accuracies in the final artificial word learning task, as well as in the generalization task. Conversely, the learning of a square and deep orthography (SD) will be correlated with one's visuospatial skills. As for the neural aspect, differences in N170 lateralization across orthography conditions are to be expected, such that the reading of square, deep orthographies, would result in more bilateralized N170 activity compared to the reading of linear, shallow orthographies, which would be more left-lateralized. With the inclusion of both pre- and post-training ERP measures in this study, it can be safely

hypothesized that group differences, if any, in pre-training N170 lateralization will be attributed solely to differences in spatial configuration, as subjects have not been taught the word-to-sound associations. In contrast, lateralization differences motivated by orthographic depth, if any, would be indexed by a shift in lateralization from pre-training to post-training N170 amplitudes. The effect that cannot be confidently predicted based on the literature, and also of utmost interest, is the interaction between the two orthographic properties at post-training. If N170 lateralization is primarily driven by orthographic transparency, there should be more left-lateralized activity for the shallow orthographies relative to the deep orthographies at post-training. On the other hand, if spatial configuration is the main determinant of lateralization, there should be more left-lateralized activity for linear orthographies relative to square orthographies.

In short, the specific hypotheses of Study One are:

- 1) Spatial configuration, and not phonological mapping, would have a significant effect over N170 laterality at pre-training.
- 2) Phonological mapping would have a significant effect over the change in N170 laterality from pre-training to post-training.
- 3) The post-training N170 laterality would reflect the interactional effect of spatial configuration and phonological mapping
- 4) The learning of scripts with different spatial configuration and phonological mapping would be correlated with different cognitive skills.

The findings in this study will uncover how these two orthographic properties individually and interactively contribute to the lateralization of the N170, and ultimately aid in verifying the predictions of the Visuo-perceptual Account and Phonological Mapping Account.

4.2 Method

4.2.1 Subjects

Seventy-six right-handed volunteers were recruited for the study. Subjects reported to be neurologically healthy with normal hearing and normal, or corrected-to-normal, vision. They were also screened for reading disability, and knowledge of logographic scripts, such as Chinese. At the point of recruitment, all subjects reported to have no knowledge of logographic scripts at all, or could read no more than a few words in a logographic script. However, *post-hoc* examination of responses to a language background questionnaire revealed that eight subjects have more than minimal knowledge of a logographic script, and were thus excluded from the data analysis. Five additional subjects' data were removed due to low signal-to-noise ratio in the ERP data, and one subject withdrew from the study prematurely, having failed to complete all five sessions. Data from 62 participants are reported here. Group characteristics are reported in Table 1 below. Ethical approval was granted by the Institutional Review Board of Nanyang Technological University, Singapore, and all subjects were fully briefed and provided written informed consent prior to the start of the study.

Table 1. Characteristics of subjects across the four artificial orthography groups with one-way ANOVA statistics. Standard deviations are in parentheses.

	LS	LD	SS	SD	F	<i>p</i>
N	15	16	17	14		
Gender (M:F)	8:7	10:6	10:7	7:7		
Age	23.9 (5.63)	24.9 (3.96)	24.2 (3.00)	22.4 (2.17)	1.134	.343
IQ ^a :	107.27 (10.78)	106.80 (9.66)	108.35 (8.51)	103.50 (8.83)	0.722	.543
Auditory Working Memory	32.93 (4.73)	34.60 (3.70)	33.47 (4.71)	33.07 (4.60)	0.428	.734

^aAssessed with Test of Nonverbal Intelligence, Fourth Edition (TONI-4)

4.2.2 Artificial Orthography Training

4.2.2.1 Materials

Artificial Orthographies. Four artificial orthographies that contrast in spatial configuration and orthographic depth were developed for this study in order to explore the effects of spatial configuration and orthographic depth on cognitive correlates and N170 laterality. The four orthographies are Linear Shallow (LS), Square Shallow (SS), Linear Deep (LD), and Square Deep (SD). The visual words in the artificial orthographies were constructed from the same set of 10 artificial letters, adapted from an African script. Four letters (𞤲, 𞤳, 𞤴, 𞤵) always appeared at the first position (left-most in Linear orthographies, and top-left in Square orthographies), two letters (𞤶, 𞤷) always appeared at the second position (middle letter in Linear orthographies, top-right

in Square orthographies), and 3 letters (𐤀, 𐤁, 𐤂) always appeared at the last position (right-most in Linear orthographies, bottom in Square orthographies). The auditory words were designed to match the visual words, such that there are 4 onset phonemes: /b/, /m/, /t/, /g/, 2 vowels /ɪ/ and /ɔ/, and 3 final phonemes: /n/, /d/, /k/. This resulted in 24 unique 3-letter visual words and 24 unique single syllable CVC auditory words.

The four artificial orthographies differed in how the visual words mapped on to the auditory words, as well as how the letters were arranged within a word. In the shallow orthographies (LS and SS), each artificial letter consistently corresponded to one phoneme. This one-to-one mapping allowed for generalization of grapheme-phoneme conversion rules to unlearned words that are composed of learnt graphemes. Two undergraduate students majoring in Linguistics with good knowledge of phonetics and phonology were asked to transcribe the auditory words into phonemes, and all words were transcribed as their intended phonemic form, ensuring that the grapheme-phoneme conversion rules could be consistently applied to the entire set of words in the shallow orthographies. In the deep orthographies (LD and SD), the correspondence between the visual words and the auditory words were randomly assigned, such that there are no predictable grapheme-phoneme conversion rules. In the linear orthographies (LS and LD), letters are arranged in a serial fashion horizontally. In contrast, words in the square orthographies (SS and SD) are made with letters packed within in a square configuration with two letters on the top and one letter at the bottom. Examples from each orthography condition are illustrated in Table 2.

Table 2. Examples of artificial words in different orthography conditions. In the shallow conditions, words contrast minimally both in the auditory and visual forms, e.g., “bok” and “gok”, which only differ in the onset phoneme, only differ in the first letter in their visual forms. In the deep conditions, there is no consistent or predictable relationship between the auditory and visual word forms, such that “bok” and “gok” differ in both the first and the third letters.

Auditory word		Spatial Configuration			
		Linear		Square	
		/bɔk/	/gɔk/	/bɔk/	/gɔk/
Orthographic Depth	Shallow
	Deep

Cognitive Tasks. Subjects performed the following tasks accessing their non-verbal intelligence, auditory working memory, phonological awareness, and visuospatial perception:

1. Test of Nonverbal Intelligence, Fourth Edition (TONI-4)

Form A of TONI-4 was administered. Subjects were asked to observe a given pattern and choose, from 4 or 6 choices, the one that best fits into the empty box in the pattern. It assesses intelligence, aptitude, abstract reasoning, and problem solving. The test would terminate when subjects had made three errors in five consecutive questions. Raw scores were then transformed into age-standardized scores.

2. Auditory Working Memory, Woodcock-Johnson Test of Cognitive Abilities

On each trial, subjects heard a sequence of 3 to 8 items consisting of nouns (e.g. animals, food, and clothing), and single-digit numbers. Subjects were instructed to rearrange the items such that all the nouns come first, in the order that they appeared in the sequence, followed by the numbers, also in the order that they appeared in the sequence. It assesses one's ability to store and manipulate items in working memory. To score a point in a trial, subjects would have to recall all the nouns and numbers accurately, and in the correct sequence. The test would terminate prematurely if the subject had failed to meet the sub-section ceiling score.

3. Test of Visual Perceptual Skills (TVPS-3)

Subtests 1-5 of the TVPS was administered. In Subtest 1, *Visual Discrimination*, subjects had to pick, from 4 options, the design that was an exact match to the target at the top. In Subtest 2, *Visual Memory*, subjects were given 5 seconds to look at a design, and were subsequently asked to recall the design among 3 other distractors. In Subtest 3, *Spatial Relations*, subjects had to pick the design that was different from the other three options. In Subtest 4, *Form Constancy*, subjects were asked to pick the option which consisted a target design; the design in the correct option can be larger, smaller, or rotated. In Subtest 5, *Sequence Memory*, subjects were given 5 seconds to memorize design sequences comprised of an increasing number of elements, and were then asked to recall the target sequence among 3 other distractors. All subtests in the TVPS had no basal and ceiling scores, and subjects were awarded one point for each correct response.

4. Visual-Auditory Learning, Woodcock-Johnson Test of Cognitive Abilities

Subjects were taught the meaning of 3 to 4 symbols at a time, and had to read sentences that were constructed of the symbols they have learnt. It assesses their ability to rapidly associate an auditory meaning with a visual symbol, and to store an increasingly large number of such mappings in their working memory. The number of errors made were recorded and used for data analysis. The test would terminate when the subject had exceeded the sub-section ceiling score (number of errors).

5. Spelling of Sounds, Woodcock-Johnson Test of Achievement

Subjects were asked to dictate nonsense words (e.g. ift, pash) to assess their ability to convert an unfamiliar auditory word form into its visual word form by observing the governing phoneme-grapheme conversion rules. Subjects were awarded one to three points for each correctly spelt nonsense word. There was no ceiling score in this task.

The first two tasks, TONI-4 and Auditory Working Memory, were used as a measure of the subjects' general cognitive abilities. Phonological skills were assessed through the Spelling of Sounds task, while visual spatial skills were assessed via the TVPS-3. The Visual-Auditory Learning task measured subjects' abilities to make a large number of symbol-to-meaning associations within a short time, which is crucial for referent mapping and successful word learning.

4.2.2.2 Procedures

General Procedures. All subjects completed the study over five consecutive days, committing about one hour each day. EEG sessions (described in detail in *EEG Data Acquisition* section below) were conducted on the first and last day. Subjects learnt a total of 18 words progressively over 5 sessions (see **Table 3** for experiment schedule). In sessions 2, 3, and 4, subjects performed cognitive tasks after completing the artificial word learning task. The order of the cognitive tasks was counterbalanced across subjects.

Table 3. Experiment schedule. Subjects learnt 18 words from the assigned artificial orthography progressively over five consecutive days, with new words introduced on the first, second, and fourth day. Revisions were scheduled on Days 2-5 to facilitate consolidation and learning

Day	Tasks (in chronological order)
Day 1	Pre-training EEG, Learn first 6 words
Day 2	Learn next 6 words, Revise first 12 words, Cognitive tasks
Day 3	Revise first 12 words, Cognitive tasks
Day 4	Learn last 6 words, Revise all 18 words, Cognitive tasks
Day 5	Revise all 18 words[#] , Generalization task (for shallow orthographies), Post-training EEG

Note. [#] The accuracy rate in this artificial word learning task was used to correlate with performance in cognitive tasks.

Artificial Word Learning Task. The artificial word learning task was done in E-Prime 2.0 (Psychology Software Tools, Pittsburgh, PA). Prior to the first artificial word learning session, subjects were told they would be learning a total of 18 words progressively over five days, without further instructions about the features of the

orthographies. In each session, subjects were shown all the words they were assigned to learn in the session, and could listen to each word's pronunciation by inputting the number shown under the word via a keypress. This implied that subjects were able to listen to any word of their choice for any number of times. They were encouraged to do so until they were confident that they have learnt the pronunciations to all the words, while keeping to the general time limit of 30 minutes. Subjects then proceeded onto the session quiz assessing their knowledge of the visual-auditory word mappings, and were encouraged to score above 70% in the quiz. At every trial in the session quiz, all words learnt in the session were shown on the screen, and subjects were tasked to match a given auditory word to the corresponding visual word. Subjects were given a maximum of 10 s to respond, after which they were given feedback ("Correct!" or "Incorrect!"), together with the correct visual and auditory word (shown regardless of trial accuracy). An example of a trial is illustrated in Figure 1. The positions of the visual words were jumbled at every trial, such that subjects would not have been able to perform the task by merely associating an auditory word with a certain position or number. Each auditory word was repeated 4 times, in random order, resulting in 24 trials for sessions that had 6 words, 48 trials in sessions that had 12 words, and 72 trials for sessions with all 18 words.

Figure 1. Example of a "correct" trial and an "incorrect" trial in the Session Quiz.

Generalization Task. Subjects in the shallow orthography groups (LS & SS) performed the Generalization Task to assess if they have successfully learnt the grapheme-phoneme mappings. The Generalization Task consisted of 6 new words that were not presented in the Learning Task. On each trial, subjects were given 4 visual words (2 new words, 2 learnt words) and were asked to choose the option that matched the auditory word played. Subjects were given a maximum of 10 s to make a response. Each new word appeared 4 times in a random order, resulting in a total of 24 trials in this task.

4.2.2.3 Behavioral Data Analysis.

Subjects' accuracies in Session 5's artificial orthography learning task where they revised all 18 words together for the last time was used as an indicator of their learning success. For the shallow conditions (LS and SS), the scores on the generalization task were used as an additional indicator to verify if subjects have successfully learnt the grapheme-phoneme conversion rules. The accuracies in these two tasks were used to correlate with subjects' performance in the battery of cognitive tasks administered to investigate if the learning of the different artificial orthographies have different cognitive correlates.

4.2.3 EEG Data Acquisition

EEG recording sessions were conducted before the first artificial orthography learning session on Day 1 (pre-training) and after the last artificial orthography learning session on Day 5 (post-training).

4.2.3.1 EEG one-back task

Subjects performed a visual one-back task during the pre-training and post-training EEG sessions, where they rapidly decided if the current stimulus on the screen was the same as the stimulus that immediately preceded it. Subjects were seated comfortably in a soundproof room, approximately 150 cm away from the monitor screen. A trial commenced with a fixation at the center of the screen (jittered duration between 1000 to 2000 ms), followed by the presentation of the stimuli, an artificial word in their assigned condition (2000 ms), during which they were asked to respond. All stimuli were presented at the center of the screen against a white background, with letter size kept constant. Subjects were instructed to respond as quickly and as accurately as

possible. The order of presentation was pseudorandomized such that there was an equal number of “same” trials and “different” trials, and there was an equal number of each artificial word in the sequence. Subjects’ responses were recorded via mouse response (*left-click* for “same”, *right-click* for “different”). There were 200 trials in the sequence and it took subjects an average of 12 minutes to complete each session.

4.2.3.2 EEG recording and preprocessing

The 64-channel EEG was recorded using a Hydrocel Geodesic Sensor Net (Electrical Geodesics Inc., Eugene, Oregon) referenced to the vertex electrode. Data was sampled at 1000 Hz/channel with calibrated technical zero baselines. Electrode impedances were kept below 50k Ω . Data preprocessing was done in EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014). Spline interpolation was applied to channels with no signal, or extremely high impedance during acquisition, and channels with excessive artifacts. The data was then referenced to the average, digitally band-pass filtered (0.3-30 Hz), and epoched from -200 ms pre-stimulus onset to 800 ms post-stimulus onset. Eye-blink components were identified and removed using Independent Component Analysis (Jung et al, 2000), and artifacts exceeding $\pm 100 \mu\text{V}$ in any channel were automatically rejected from further analyses. After baseline correction (-200 to 0 ms), averaging was done for each dataset. Grand means were then computed for each artificial orthography condition, and at each session (pre- and post-training).

4.2.3.3 EEG data analysis

The N170 time window of 150 ms to 210 ms was identified selecting a time frame $\pm$ 30 ms from N170 peak after averaging all grand means (averaged over all four artificial orthography conditions, pre- and post-training), which was at 180 ms (see Fig. 4 on pg. 62 for ERP waveforms at occipitotemporal electrodes). In accordance with the hypotheses made, three separate analyses were performed: 1) pre-training and 2) post-training N170 peak amplitude, and 3) change in N170 peak amplitude from pre-training to post-training. For all analyses, a three-way mixed-design ANOVA was performed on the peak amplitudes at four occipitotemporal electrodes (Left occipitotemporal electrodes (LOT): E30 and E32; Right occipitotemporal electrodes (ROT): E43 and E44; channel locations illustrated in Fig 2), with *hemisphere* (left vs. right) as a within-subject factor, and *orthographic depth* (shallow vs. deep), and *spatial configuration* (linear vs. square) as between-subject factors. For the pre-training analyses, data from all 62 subjects are reported. For the post-training and change from pre-training to post-training analyses, only subjects who scored above 70% in the final artificial word learning session, and those who scored above 70% in the generalization task in the shallow conditions were included. This allowed us to fairly compare the N170 lateralization among subjects who had achieved similar levels of learning success, which could otherwise be a confounding variable. This resulted in a final sample of 53 subjects (14 in LS and SS, 13 in LD, 12 in SD) for the latter 2 analyses.

Figure 2. Sensor layout of the 64-channel Hydrocel Geodesic Sensor Net. Data for the analyses were obtained from LOT electrodes (E30 & E32, corresponding to P7 & PO7 in 10-20 system), circled in red and ROT electrodes (E43 & E44, corresponding to P8 & PO8), circled in blue.

In addition, a lateralization index was computed by subtracting the peak N170 amplitude in the ROT from that in the LOT to aid in data visualization (i.e. Laterality Index (LI) = $\text{PeakAmplitude}_{\text{LOT}} - \text{PeakAmplitude}_{\text{ROT}}$; e.g., Stevens et al., 2013; Spironelli, Penolazzi, & Angrilli, 2010). A negative value in the index indicates left-lateralization, and vice versa for a positive value; a value close to 0 indicates bilateralization.

4.2 Results

4.3.1 Overall Learning Performance

Subjects attained high levels of accuracy at the end of the training, indexed by *Session 5 accuracy*, scoring 85.8% on average. A boxplot illustrating Session 5 Accuracy across artificial orthography conditions is shown in Figure 3. A one-way ANOVA revealed significant group differences [$F(3, 59) = 4.187, p < 0.01$]. *Post-hoc* comparisons (Bonferroni corrected) indicated a significant difference only between the LS ($M = 93.6\%$, $SD = 8.1$) and the LD group ($M = 79.6\%$, $SD = 11.7$). For the shallow conditions (LS and SS), subjects scored an average of 92% in the generalization task, suggesting good knowledge of the grapheme-to-phoneme rules governing the artificial orthography learnt. Spatial configuration did not influence subjects' ability to generalize [$t(28) = .774, p = .445$].

Figure 3. Accuracy rates across artificial orthography conditions in Session 5 (last session). * $p < .01$.

4.3.2 Cognitive correlates of learning performance

Planned Pearson's correlations (2-tailed) were performed to uncover the cognitive skills that were correlated with the learning performance in the different artificial orthography conditions (results reported in Table 4). Significant correlations were observed between the Session 5 accuracy in the two square conditions (SS and SD), and performance in the Visual-Auditory Learning task (SS: $r = -.491$, $p < 0.05$; SD: $r = -.860$, $p < .001$). The Visual-Auditory Learning task is scored based on number of errors that were made, which means that better performers would have scored lower, resulting in the negative correlations observed. In addition, learning performance in the SD condition also correlated with the composite score of subtests 1 to 5 on the Test of Visual Perceptual Skills ($r = .702$, $p < .01$). No other correlations turned up significant.

Table 4. r -coefficients of correlations between word learning performance (as indicated by Session 5 accuracy) and cognitive tasks performance across groups.

	Spelling of sounds	TVPS [#]	Visual-auditory learning
Linear shallow	.232	.063	-.041
Linear deep	.061	-.080	-.092
Square shallow	.181	.170	-.491*
Square deep	-.075	.702**	-.860***

Note: * $p < .05$, ** $p < .01$, *** $p < .001$. [#] composite score of TVPS subtest 1 to 5.

4.3.3 ERP Results

The ERP waveforms at occipitotemporal electrodes (averaged) across artificial orthography conditions and at each time point are illustrated in Figure 4 below. Numerical values of mean N170 amplitudes are reflected in Table 5.

Figure 4. ERP waveforms averaged across bilateral occipitotemporal electrodes (E30, E32, E43, E44) across artificial orthography conditions and across pre- and post-training. N170 time window boxed up in blue.

Table 5. Mean peak N170 amplitudes (μV) for different orthography groups at pre-training and post-training. LS = Linear Shallow, LD = Linear Deep, SS = Square Shallow, SD = Square Deep. LOT = Left occipitotemporal electrodes (E30 & E32), ROT = Right occipitotemporal electrodes (E43 & E44).

Session	Group	N	LOT (SD)	ROT (SD)	L-R (SD)
Pre-training	LS	15	-2.16 (2.81)	-1.82 (2.67)	-0.34 (1.08)
	LD	16	-2.49 (1.46)	-1.41 (1.49)	-1.07 (1.56)
	SS	17	-1.38 (0.86)	-1.81(1.69)	0.43 (1.45)
	SD	14	-1.46 (2.65)	-1.53 (1.70)	0.07 (1.58)
Post-training	LS	14	-2.88 (2.05)	-2.04 (1.47)	-0.84 (1.50)
	LD	13	-3.13 (2.36)	-2.62 (1.50)	-0.51 (1.98)
	SS	14	-2.15 (1.29)	-2.50 (1.89)	0.35 (1.35)
	SD	12	-2.67 (3.56)	-2.83 (2.78)	0.15 (1.77)

The grand ANOVA of *session* $\times$ *hemisphere* $\times$ *orthographic depth* $\times$ *spatial configuration* ($N = 53$) returned a significant main effect of *session* [$F(1, 49) = 6.371, p = .015, \eta^2 = .115$], indicating that post-training N170 amplitudes were significantly more negative than those of pre-training [Pre-training: $M = -1.96, SD = 1.85$, Post-training: $M = -2.60, SD = 2.03$], reflecting increased familiarity and expertise for the learned stimuli. There is also a significant interaction effect of *hemisphere* $\times$ *spatial configuration* [$F(1, 49) = 5.496, p = .023, \eta^2 = 0.101$], suggesting that across sessions, N170 laterality was shaped by spatial configuration, such that subjects in linear groups elicited left-lateralized N170 [LOT: -2.72 vs ROT: -2.03] activity while it's considerably more bilateralized for subjects in square groups [LOT: -2.10 vs ROT: -

2.29]. No other effects were significant, although there was a trend of *session* $\times$ *hemisphere* $\times$ *orthographic depth* interaction effect [$F(1, 49) = 3.267, p = .077, \eta^2 = 0.063$]. This signifies that the change in N170 laterality from pre-training to post-training tended to be of different polarities for subjects in shallow and deep conditions.

The following sections will report the findings from the three planned ANOVAs reflecting effects at pre-training, post-training, and changes from pre-training to post-training respectively.

4.3.3.1 Pre-training Lateralization Effects

At pre-training, a mixed-design ANOVA of *hemisphere* $\times$ *orthographic depth* $\times$ *spatial configuration* revealed only a significant interaction effect of *hemisphere* $\times$ *spatial configuration* [$F(1, 58) = 6.203, p = .016, \eta^2 = 0.097$], suggesting that at pre-training, only spatial configuration significantly shaped the lateralization of the N170 component. In *post-hoc* comparisons, while the peak N170 amplitude on the left was significantly more negative than that in the right for the linear conditions, the two did not differ significantly in the square conditions [For linear conditions, LOT: $M = 2.49, SD = 2.04$; ROT: $M = -1.79, SD = 1.91$; $t(29) = -2.74, p = .010$. For square conditions, LOT: $M = -1.41, SD = 2.00$, ROT: $M = -1.58, SD = 1.92$; $t(31) = 0.660, p = .514$].

Visualizing this in terms of Lateralization Index (LI), in the linear conditions, the LI is -0.719 ($SD = 1.38$), with its negative polarity indicating left-lateralization. This

is significantly different from the square conditions, with a LI of 0.219 (SD = 1.49). The topographic maps illustrating the different lateralization patterns are shown in Figure 5.

Figure 5. Topographic maps at $t = 180$ ms for Linear (LS & LD; left) and Square (SS & SD; right) conditions. The posterior negativity is more left-lateralized for Linear conditions, and generally bilateralized for Square conditions ($p < .05$).

4.3.3.2 Post-training Lateralization Effects

At post-training, spatial configuration remains the only factor that influenced N170 lateralization, with the interaction of *spatial configuration* $\times$ *hemisphere* the only effect that reached significance [$F(1, 49) = 4.139$, $p = .047$, $\eta^2 = 0.078$]. Similar to effects observed at pre-training, this interaction is driven by a significant left-lateralization in the linear conditions, and bilateral negativity for the square conditions [For linear conditions, LOT: $M = -3.00$, $SD = 2.17$; ROT: $M = -2.32$, $SD = 1.49$; $t(26) = -2.063$, $p = .049$. For square conditions: LOT: $M = -2.39$, $SD = 2.55$; ROT: $M = -2.65$, $SD = 2.30$; $t(25) = 0.860$, $p = .398$]. The topographic maps illustrating the differences in N170 lateralization at $t = 180$ ms across all four orthography groups are shown in Figure 6.

Figure 6. Topographic maps at $t = 180$ ms for the four artificial orthography conditions at post-training.

4.3.3.3 Post-training Lateralization Change

As mentioned earlier in the grand ANOVA findings, a *near* significant interaction effect of *session* $\times$ *hemisphere* $\times$ *orthographic depth* [$F(1, 49) = 3.463, p = .077, \eta^2 = .063$] was observed, signifying that there was a trend that the change in lateralization tended to be different for the shallow and deep conditions. Examination of the change in lateralization index (plotted in Figure 7) showed that while the learning of shallow orthographies (LS and SS) resulted in a left-ward shift in lateralization post-

training (from 0.41 (SD = 1.32) pre-training to -0.25 (SD = 1.53) post-training), the deep orthographies (LD and SD) differed by resulting in a right-ward shift in lateralization post-training (from -0.63 (SD = 1.64) pre-training to -0.19 (SD = 1.81) post-training). This effect, however, appears to be stronger in the linear conditions.

Figure 7. Change in Lateralization Index (LI), computed by subtracting pre-training LI from post-training LI. Error bars represent standard error.

4.4 Discussion

Findings from cognitive correlates and N170 lateralization patterns converge to show that orthographic transparency and spatial configuration both play an important role in determining the cognitive and neural processes involved in reading. In particular, the findings in this study highlighted the role of spatial configuration in motivating both cognitive correlates and N170 lateralization. Visual-auditory learning skills were associated with word learning performance only in the two square orthographies (SS and SD), suggesting that the ability to map symbols to a sound is crucial for the learning of square, but not linear, orthographies. Neurally, significant main effects were only observed for spatial configuration, where linear orthographies elicited significantly more left-lateralized N170s than square orthographies. While there were no significant effects related to orthographic depth alone, the findings in N170 lateralization demonstrated a tendency for shallow orthographies to undergo left-ward shifts from pre-training to post-training, while deep orthographies undergo right-ward shifts. Effects of spatial configuration and orthographic depth also seem to be interactive in nature. Firstly, it was observed that only the learning of a square and deep orthography (SD) relied on visual spatial skills, which were less crucial in the learning of linear or shallow orthographies (LS, LD, SS). This suggests that neither spatial configuration nor orthographic depth, on their own, could motivate the relationship between learning performance and visual spatial skills. Secondly, while the direction of shift in lateralization from pre-training to post-training seemed to be influenced by orthographic depth, the extent of shift was possibly further modulated by spatial configuration, again demonstrating the interactive nature of the two factors.

4.4.1 Different Orthographic Properties, Different Processing Demands

Out of the four artificial orthography conditions, only the learning of Square Deep (SD) was crucially associated with visual spatial skills, such that those with better visual spatial skills (as assessed with TVPS-3) excelled in the final word learning task. For linearly constructed orthographies as well as the orthography that was square but not deep (Square Shallow (SS)), visual spatial skills did not have a significant influence on subjects' word learning performance. In other words, neither being in a square configuration nor being orthographically opaque alone could motivate the relationship between visual spatial skills and word learning performance. This demonstrates the interactive nature of orthographic transparency and spatial configuration in determining the cognitive skills required to master the visual-to-auditory mappings in a language. The importance of visual skills for reading in a deep and nonlinear orthography, such as Chinese, is a topic of debate, with some concluding that visual skills positively relate to Chinese reading (e.g., Huang & Hanley, 1995; Ho & Bryant, 1997; Luo et al., 2013; McBride-Chang et al., 2005; Siok & Fletcher, 2001), and others finding no association between the two (Ho, 1997; Hu & Catts, 1998; McBride-Chang & Ho, 2000; McBride-Chang & Kail, 2002). Of note, McBride-Chang et al. (2005) administered three tasks of visual skills and found that the Visual-Spatial Relations task, which required subjects to select the item which was different from the other options, was a better predictor of reading abilities over the other two tasks, which assessed visual closure, and visual matching, suggesting that certain components of visual skills are more relevant to Chinese reading than others. In a later opinion article by Zhou, McBride-Chang, and Wong (2014), three visual skills were named as the most likely to be required for Chinese reading: 1) visual form constancy, identifying a visual form as its size changes, 2) visual-spatial skills, identifying a visual form when it is of a different orientation, and

3) visual memory, which encompasses making associations between characters and sounds, and remembering how different parts are located relative to one another within a single character. Upon closer examination of the relationships between subjects' scores in the subtests of TVPS-3 and word reading performance in our sample, it was found that out of the five subtests, 3 tasks had significant correlations to the word reading performance – Subtest 1: Visual Discrimination, Subtest 2, Visual Memory, and Subtest 4: Form Constancy. Of these, the Form Constancy subtest tapped on subjects' abilities to identify a visual form when its size and/or orientation had changed, thus involving the first two skills mentioned by Zhou and colleagues. The last skill, visual memory, was assessed in both Subtest 2 and in the Visual-Auditory Learning Task, with the former relating to the ability to remember a visual form and discriminating it from other similar items, and the latter relating to the ability to make associations between symbols and sounds. Since the Square Deep script in this study is orthographically similar to Chinese, the present findings lend support to Zhou and colleagues' proposal that visual form constancy, visual-spatial skills, and visual memory are necessarily recruited for Chinese reading. This study further finds that visual memory skills are important for scripts in which characters are squarely-constructed, regardless of the orthographic depth.

Another under-researched and related issue is the nature of causality between visual skills and Chinese reading acquisition. While earlier studies tended towards the argument that one is the consequence of the other, later studies favored the notion of bidirectional association between the two, where visual skills are facilitative towards the development of Chinese reading acquisition and *vice versa*. The present findings likely demonstrate a unidirectional facilitative effect of visual skills on “Chinese”

reading as the visual skills tasks were not administered as a post-test, and could have taken place between the second day to the fourth day of training. It thus seems more probable that the visual skills exhibited were not consequents of the artificial word learning. With that said, it should be recognized that there may exist a bidirectional facilitative relationship which may be more well-captured in a longitudinal study.

Contrary to initial predictions, word learning performance in shallow orthographies did not correlate with phonological skills, regardless of linearity. The use of native phonemes combined with simple phoneme-grapheme conversion rules may have greatly reduced demands on phonological processing, such that subjects with varying levels of phonological competence were all able to do so, as indicated by high accuracy rates in the generalization task. In the literature, it has been suggested that while phonological awareness is a good predictor of reading abilities in English, it may be a weaker predictor in scripts with relatively more transparent orthography, such as German and Dutch, as individual differences in phonological skills are overridden by the highly consistent grapheme-phoneme mappings (e.g., de Jong & van der Leij, 2002; Wimmer et al., 2000).

4.4.2 Different Orthographic Properties, Different N170 Lateralization Patterns

N170 lateralization differences were observed at pre-training, which were driven by differences in spatial configuration. This matches with the prediction that any lateralization differences at pre-training would be solely attributed to spatial configuration, as subjects would still be naïve to the word-to-sound mappings. Specifically, squarely-constructed orthographies elicited a bilateral N170 response,

while linearly-constructed orthographies were associated with left-lateralized N170 activities. The effects of spatial configuration on N170 lateralization persisted at post-training, demonstrating its robustness, in the sense that it was not limited to unfamiliar stimuli. This finding seemingly sits well with the predictions of the Visuo-perceptual Account, which specifies that the left hemisphere's preference for linear processing and the right hemisphere's for configural processing would result in greater left-lateralized responses for a linear orthography, in comparison to a square orthography. It is also plausible that the artificial orthographies in the linear construction were processed as "3-letter words", which encouraged individual identifications of component letters, thus engaging detail processing, and therefore the left hemisphere, to a greater extent. In contrast, orthographies of a square configuration may have been processed as single characters, thus engaging holistic processing, which tends to tax the right hemisphere.

Contrary to past findings, effects of orthographic transparency on N170 lateralization at post-training were not replicated in this study. Previous artificial orthography training studies have demonstrated that the learning of a deep orthography should result in bilateral N170 activity, in contrast with a left-lateralized pattern for linear orthographies. The present study instead found that spatial configuration remained the sole driving force of lateralization differences at post-training. This may be due to differences in training paradigms between the current study and previous ones. As pointed out in Chapter 3, nearly all past artificial orthography training studies had subjects in different orthography conditions undergo different trainings. It was common for phoneme-grapheme conversion rules in the shallow orthographies to be made explicit and subjects performed tasks to enhance their knowledge of those rules, while subjects learning the deep orthographies were assigned tasks that encouraged the

memorization of whole-words. Such differences in training paradigms may have resulted in more dramatic differences in OT/N170 laterality compared to this study, which did not highlight the phonological mapping rules and instead had subjects across groups undergo the same training. In other words, past artificial orthography studies may have observed greater left-lateralization for shallow orthographies partly because directing attention to individual letters within a word may have demanded more detail processing, thereby increasing left hemisphere involvement. As mentioned earlier, one main research gap this study aimed to fill is to isolate effects that are motivated by the inherent orthographic properties, rather than different instructional methods. In natural language acquisition, readers of shallow orthographies may not always begin reading instruction with systematic phonics instruction, and may learn as readers of deep orthographies would – by making sound-to-sound associations repeatedly. As vocabulary size increases, readers of shallow orthographies would then begin to spot regularities and gain knowledge of grapheme-phoneme conversion rules, while readers of deep orthographies still rely on rote memory primarily. The present study attempted to emulate such a form of natural language acquisition, and found that when subjects were not trained differently, orthographic depth did not seem to have significant effects on N170 lateralization.

However, this is not to say that orthographic transparency had zero influence over N170 laterality. There was a trend for shallow orthographies to have a left-ward shift in N170 laterality at post-training, relative to pre-training, while deep orthographies tended to have a right-ward shift. This is somewhat compatible with previous findings that shallow orthographies have greater left-lateralization than square orthographies. Therefore, the pattern of results in this study should be considered a muted version of,

rather than contradictory to, past findings. Again, the lack of explicit grapheme-phoneme conversion instruction in this study may have been the main reason for the weak orthographic depth effects observed. Interestingly, there is a possibility that the effects of orthographic transparency on lateralization change are further modulated by spatial configuration. Although not statistically significant, visual inspection of the data leads to the observation that effects of orthographic transparency are relatively clearer in the linear orthographies than in the square. In the linear groups, the N170 laterality changed in opposite directions for the shallow and deep orthographies, whereas for the square groups, the deep orthography had a slight shift to the RH, while the laterality for the shallow orthography remained unchanged. A closer inspection of N170 amplitude changes within each hemisphere revealed that the differences between Linear Shallow and Linear Deep were mainly driven by reduced increase in N170 amplitudes in the RH for Linear Shallow. In contrast, for the square orthographies, the N170 amplitudes in both hemispheres increased (became more negative) by similar magnitudes. In other words, LH activity increased regardless of orthographic transparency for both spatial configurations. On the other hand, increase in RH activity was sensitive to orthographic transparency, but only in the linear orthographies. In the square orthographies, RH activity did not differ between square and shallow conditions. This suggests that the absence of LH shift in the Square Shallow group is possibly attributed to greater demands on RH, likely due to its square configuration.

4.4.3 Limitations and Interim Conclusion

In attempt to keep training procedures across groups as identical as possible, other measures had to be put in place to ensure satisfactory learning performance. In particular, subjects were allowed to revise the sound-to-word mappings as many times

as they wished, within a general time limit of 30 minutes per session. They were also encouraged to attain an accuracy rate of over 70% in every session. Such measures may have led to reduced variance in performance across subjects, and that may be a possible cause for the lack of significant correlations between the learning of linear and shallow orthographies with the cognitive tasks administered. In a pilot study (not reported in this thesis) where subjects learned artificial words with a fixed number of presentations, large variability in subjects' performance was observed, both within conditions and between conditions. Importantly, there were more significant correlations between subjects' learning performance and the scores on the cognitive tasks, which were not seen in Study One. Therefore, it can be speculated that more and stronger correlations would have been observed if the amount of exposure to the artificial words was restricted.

Next, the use of a perceptual task (the one-back task) may also have contributed to non-significant effects of orthographic depth on N170 lateralization. Although a large number of studies have utilized the one-back task in investigating N170 effects in visual word processing, it has been suggested that lateralization differences may not surface when the task does not require active language processing (e.g., reading verification task), especially when subjects have not achieved sufficient expertise for the visual words (Maurer et al., 2010; Yoncheva et al., 2015). Even though the subjects in this study have attained high levels of accuracy in the artificial word learning tasks, the amount of exposure and expertise for the artificial words pales in comparison to what one would have for a native language. However, it needs to be reiterated that there was a trend for orthographic depth to influence the direction of lateralization shift, in a manner that concords with previous studies. It thus seems that orthographic depth effects

can be observed, albeit weakly, with a perceptual task. The stronger orthographic depth effect on N170 lateralization elicited by a language task have been cited as an evidence for the Phonological Mapping Account. In a reading verification task, for example, subjects in a shallow orthography condition are hypothesized to engage grapheme-phoneme mapping processes, while subjects in a deep orthography condition likely engage a whole word mapping process. This difference in mapping strategies then translates into greater left-lateralized N170 activity for shallow orthographies than for deep orthographies, supporting the notion that the left-lateralized N170 in visual word processing represents phonological mapping processes. Nonetheless, greater orthographic depth effects elicited by active language tasks relative to perceptual tasks could also be explained from the Visuo-perceptual perspective, which would attribute such effects to the need to pay greater visual attention to details (i.e., individual letter identities) in a shallow orthography when the task explicitly calls for access to phonology, thereby resulting in more a left-lateralized N170 activity.

In sum, findings from Study One demonstrated strong spatial configuration effects and relatively weak orthographic depth effects on cognitive and neural correlates of novel word learning. Learning of a square orthography, in particular one that is both square and deep, was associated with various subcomponents of visual skills, and was characterized by bilateral N170 activity. On the other hand, learning of a linear orthography did not critically involve visual skills, and was characterized by a left-lateralized N170. Effects of orthographic depth were only weakly manifested in the change of N170 laterality, and more so in the linear group. These findings together suggest that, at least for beginner learning different scripts in a similar manner, the N170 laterality in word reading is mainly driven by the visual spatial properties of scripts, and

at the same time it is weakly modulated by orthographic mapping principles. Considering that the Visuo-perceptual Account predicts that both visual appearance and phonological mapping rules would influence N170 laterality while the Phonological Mapping Account predicts that the more shallow orthographies would be more left-lateralized in the N170, the findings in Study One favor the Visuo-perceptual Account to a larger degree.

Chapter 5:

Study Two: A Closer Look at Coarse and Fine N170 Print Tuning Effects

5.1 Overview

This study sets out to closely examine the two N1 print tuning effects described in the literature: 1) Coarse print tuning, characterized by larger N170s for orthographic stimuli than for visual controls, and 2) Fine print tuning, referring to further N170 differences within orthographic stimuli (e.g., words vs. pseudowords vs. nonwords). In general, coarse N1 print tuning effects are more well-validated than fine N1 print tuning effects. Greater N170 amplitudes for orthographic stimuli than for symbols are commonly reported (e.g., Maurer & McCandliss, 2008; Rossion et al., 2002; Cao et al., 2011; Maurer et al., 2005; Tong et al., 2016; Eberhard-Moscicka et al., 2015). However, the coarse N1 print tuning effects can be diminished when the visual control is well-matched with the orthographic stimuli on low-level visual features (Brem et al., 2013; Xue et al., 2008). There are even greater discrepancies among findings on fine N1 print tuning effects, with studies reaching different conclusions regarding the presence and direction of tuning. To test the print selectivity and sensitivity of the N170, subjects in the present study performed a one-back task with a variety of stimuli (shown in Table 4) that differs in word-likeness on various levels while their electrophysiological activity was measured.

Table 6. Example item from each stimulus type. Greater N170 amplitudes for orthographic stimuli (boxed in red) than for non-orthographic stimuli (boxed in blue) would be indicative of coarse N1 print tuning effects. Further distinctions in N170 amplitudes within orthographic stimuli would be indicative of fine N1 print tuning effects.

	Orthographic Stimuli			Non-orthographic Stimuli	
	Word	Pseudoword	Nonword	Symbol	Artificial Word
Linear	BUN	BUL	UNB	} < %	Ψ Ƨ Ƨ
Square	BU N	BU L	UN B	} < %	Ψ Ƨ Ƨ

Since N170 amplitudes are known to increase with familiarity, it is predicted that N170 amplitudes for *artificial words* would be the weakest, since they would be novel to the subjects. Conversely, largest amplitudes would be elicited for the most familiar stimuli – *words*. For print tuning effects, greater left-lateralized N170 activity for orthographic stimuli (*words* and *nonwords*) than for *symbols* and *artificial words* would be indicative of coarse N1 print tuning effects. Further differences in lateralization patterns within the orthographic stimuli (*words*, *pseudowords*, and *nonwords*) would demonstrate fine N1 print tuning effects. If N170 is sensitive to lexicality, there should be greater N170 activity for *words* than for *pseudowords* and *nonwords*. In contrast, if N170 is sensitive to orthographic regularity but not lexicality, there would be greater N170 amplitudes for *words* and *pseudowords* than for *nonwords*, with no further difference between the former two. Lastly, if N170 reflects phonological

mapping processes, greater N170 amplitudes for *pseudowords* than for *words* would be observed, as *pseudowords* are likely to engage grapheme-phoneme mapping processes to a larger extent.

This study also takes the opportunity to investigate if effects of spatial configuration on N170 lateralization observed in Study One can be extended to other types of words and symbols which subjects have extensive experience with. This is achieved via the inclusion of both linear and square constructions across all stimulus types. If effects of spatial configuration persist when familiar stimuli are used, it would suggest that N170 laterality truly reflects differences in visual processing demands, independent of expertise level. On the flip side, if spatial configuration effects cannot be replicated when familiar stimuli are used, it could suggest that N170 lateralization reflect different processes when level of expertise is varied. At lower levels of expertise, N170 lateralization may be primarily motivated by visuoperceptual differences. In contrast, with greater expertise, N170 lateralization may be reflective of higher-level cognitive processes, such as orthographic processing, or phonological mapping. With the employment of stimuli of varying degrees of word-likeness, familiarity, and of different spatial configurations, the findings from this study would aid in furthering our understanding of N170 lateralization effects in visual word processing and their interpretations.

To further probe the relationship between N170 lateralization effects and visuoperceptual vs. phonological mapping processes, the cognitive correlates of coarse and fine print tuning effects were also examined. As mentioned in the literature review,

a line of developmental studies has shown that the coarse print tuning effects can be predictive of, or correlated, with one's reading abilities, phonological awareness, and visual skills. Such correlations have also been observed in children and adult neoliterates, but little is known about the relationship between print tuning and cognitive abilities in typical, proficient adult readers. To fill this gap in the literature, subjects' scores on tasks assessing phonological awareness and visuospatial skills were correlated with the magnitude of coarse and fine print tuning effects. Since coarse print tuning mainly taps on one's ability to distinguish words from other types of visual stimuli, it is hypothesized that coarse print tuning effects would correlate with visuospatial skills. On the other hand, fine print tuning relates to one's ability to detect well-formed letter sequences, and thus is predicted to correlate with phonological mapping skills.

In sum, the specific hypothesis of Study Two are:

- 1) Coarse and fine print tuning effects would be observed within the N170 time window.
- 2) Spatial configuration would have an effect on N170 laterality, such that linear stimuli would elicit more left-lateralized N170 than square stimuli
- 3) Magnitude of print tuning effects would be correlated with performance in cognitive tasks. Specifically, coarse print tuning would be related to visuospatial skills, and fine print tuning would be related to phonological skills.

Through examining the N170 lateralization patterns for different stimuli types and the cognitive correlates of the print tuning effects, the present study hopes to achieve a better understanding of what N170 lateralization represents in visual word processing.

5.2 Method

5.2.1 Subjects

Thirty-five right-handed volunteers were recruited for the study. Subjects reported to be neurologically healthy with normal hearing and normal, or corrected-to-normal, vision. They were also screened for reading disability as an exclusion criterion. All subjects were proficient in both English and Mandarin Chinese. Four subjects' data were removed due to low signal-to-noise ratio, two due to erroneous EEG recording, and one due to excessive movement-related artefacts. This resulted in a final sample of 28 subjects (mean age: 22 yo; 15 women). Ethical approval was granted by the Institutional Review Board of Nanyang Technological University, Singapore, and all subjects were fully briefed and provided written informed consent prior to the start of the experiment.

5.2.2 Materials

EEG Stimuli. There were five categories of stimuli differing in word-likeness and familiarity. Of these five categories, three were orthographic stimuli made of English letters: *word* (pronounceable, meaningful letter strings), *pseudoword* (pronounceable, non-meaningful letter strings), and *nonword* (unpronounceable, non-meaningful letter strings). The remaining two categories were *symbol*, and *artificial word*. The symbols were constructed with familiar alphanumeric symbols and punctuations (e.g., \$%#@!), while the artificial words were a subset of stimuli used in Study One, which were

constructed from characters in an African script. All items across categories were made of 3 letters/symbols. For each stimulus category, there was a linear construction and a square construction. This resulted in a total of 10 types of stimuli. An example from each stimulus type is shown in Table 6 on pg. 80.

Cognitive Tasks. Subjects performed the following tasks accessing their phonological awareness and visuospatial perception:

1. Spelling of Sounds, Woodcock-Johnson Test of Achievement

Subjects were asked to dictate nonsense words (e.g. ift, pash) to assess their ability to convert an unfamiliar auditory word form into its visual word form by observing the governing phoneme-grapheme conversion rules. Subjects were awarded one to three points for each correctly spelt nonsense word. There was no ceiling score in this task.

2. Sound Blending, Woodcock-Johnson Test of Cognitive Abilities

Subjects were presented building units of a single real word (syllables or phonemes) and were asked to blend the units together and sound out the target word. The number of units increased as the task progressed. Subjects were awarded one point for each correct response. The task would terminate if subjects had failed to meet the sub-section ceiling scores.

3. Spatial Relations, Woodcock-Johnson Test of Cognitive Abilities

Subjects were asked to identify the pieces that formed a target shape, which increased in visual complexity as the task progressed. Subjects scored a point for each piece that was correctly identified. There were also sub-section ceiling scores to be met in this task.

4. Picture Recognition, Woodcock-Johnson Test of Cognitive Abilities

Subjects were given 5 seconds to memorize a group of pictures and were then asked to pick out a subset of the memorized pictures among visually similar distractors. As the task progressed, both the number of the pictures to be memorized and the subset to be recalled increased. Subjects were awarded a point for each correctly recalled object, and had to meet the sub-section ceiling scores to proceed in the task.

5.2.3 Procedures

5.2.3.1 EEG Data Acquisition

EEG one-back task. Subjects performed a visual one-back task during the EEG session, where they rapidly decided if the current stimulus on the screen was the same as the stimulus that immediately preceded it. The task was split into two runs, with the order of the runs counterbalanced across subjects. In each run, the trials were blocked such that subjects were presented with all 30 trials from 1 of the 10 stimulus types (5 stimulus categories $\times$ 2 spatial configurations) before moving on to the next block of another stimulus type. There was a 10 s break in between blocks. The order of the blocks within each run was randomized. The sequence of stimulus presentation within each

block was kept constant for all 10 stimulus types to control for trial history. For example, the second item would differ from the first item in the left-most (top-left in square configuration) letter/symbol for all the blocks. There was also an equal number of “same” trials and “different” trials, and there was an equal number of each item in the sequence.

During the task, subjects were seated comfortably in a soundproof room, approximately 150 cm away from the monitor screen. A trial commenced with a fixation at the center of the screen (jittered duration between 1000 to 2000 ms), followed by the presentation of the stimuli (800 ms), during which they were asked to respond. All stimuli were presented at the center of the screen against a white background, with letter size kept constant. Subjects were instructed to respond as quickly and as accurately as possible. Subjects’ responses were recorded via mouse response (*left-click* for “same”, *right-click* for “different”). The entire one-back task consisted of 600 trials (60 for each stimulus type), and took about 30 minutes to complete (14 min for each run on average, with a short break between runs in which impedance checks were performed).

5.2.3.2 EEG recording and preprocessing

The EEG recording and preprocessing procedures were largely similar to that in Study One (detailed in Section 4.2.3.2) with two exceptions: 1) For each subject, the EEG data for the two runs were preprocessed separately before they were merged, and 2) As Study Two adopts a within-subject design, group grand means were computed for each stimulus type.

5.2.4 Data Analysis

5.2.4.1 General Analysis

An overall repeated-measures ANOVA of 2 (*spatial configuration: linear vs. square*) $\times$ 5 (*stimulus type: words vs. pseudowords vs. nonwords vs. symbols vs. artificial words*) $\times$ 2 (*hemisphere: LH vs. RH*) was performed on the N170 mean amplitudes to explore general main and interaction effects. Of particular interest were signs of N1 tuning as indexed by a significant *stimulus type* $\times$ *hemisphere* interaction, as well as effects of spatial configuration on N170 laterality.

5.2.4.2 Analysis on Print Tuning Effects

If there was a significant *stimulus type* $\times$ *hemisphere* interaction, additional analyses would be performed to investigate N1 tuning effects. First, to investigate coarse N1 tuning effects, 3 (*stimulus type: words/nonwords(characters) vs. symbols vs. artificial words*) $\times$ 2 (*hemisphere: LH vs. RH*) repeated-measures ANOVAs were performed to verify if the N170 is significantly more left-lateralized for words/characters (nonwords) than for symbols and artificial words. Second, to investigate fine N1 tuning effects, a 3 (*stimulus type: words vs. pseudowords vs. nonwords*) $\times$ 2 (*hemisphere: LH vs. RH*) repeated-measures ANOVA was performed to discern if N170 laterality is sensitive to lexicality and orthographic regularity. Wherever an interaction involving *hemisphere* turned up significant, separate ANOVAs were done for each hemisphere to further investigate inter-hemispheric differences.

5.2.4.3 Lateralization Index

In addition, a lateralization index was computed by subtracting the mean N170 amplitudes in the ROT from that in the LOT to aid in data visualization. A negative value in the index indicates left-lateralization, and vice versa for a positive value; a value close to 0 indicates bilateralization.

5.2.4.4 Selection of time windows

From inspection of the Mean Global Field Power (GFP) plot, the N170 time window of 141 to 214 ms, with a peak at 178 ms was identified. Two other peaks were apparent in the data: one at 122 ms and the other at 259 ms, corresponding to the P100 (80 – 141 ms) and P200 (214 – 280 ms) ERP components respectively. As the N170 peaks were observed maximally at occipitotemporal electrodes (E30, E32 in LH, E43, E44 in RH), mean amplitudes from these four electrodes were used for statistical analyses. The GFP plot, together with topographic maps at the three spectral peaks, are illustrated in Figure 8.

Figure 8. Global Field Power plot illustrating three spectral peaks in the grand mean across subjects and stimuli types. The three peaks are at 122 ms, 178 ms, and 259 ms, corresponding to P1, N1, and P2 respectively, as illustrated by the topographic maps. The N170 time window is outlined in blue.

5.2.4.5 Supplementary Analyses

Data analyses on the P100 and P200 components were done in a similar fashion to investigate early print tuning effects. For these two components, the polarity of the Lateralization Index is reversed, such that a positive value indicates left-lateralization, while a negative value indicates right-lateralization.

5.3 Results

5.3.1 General ERP Waveforms

It was immediately clear from visual inspection of the ERP waveforms (shown in Figure 9 below) that the patterns of activation are distinct for different stimulus types, especially in the P200 time window, suggestive of early print tuning effects.

Figure 9. ERP waveforms averaged over 28 subjects, and over occipitotemporal electrodes (E30, E32, E43, E44, corresponding to P7, PO7, P8 PO8 in 10-20 system), collapsed over spatial configuration. Stimuli made of English letters are in red (solid: word, dashed: pseudoword, dotted: nonword), blue for symbols, and black for artificial words.

5.3.2 N170 (141 – 214 ms)

5.3.2.1 Overall ANOVA

Effects of Spatial Configuration. The overall repeated measures ANOVA of *configuration* $\times$ *stimuli type* $\times$ *hemisphere* returned multiple significant effects. Starting with effects involving *spatial configuration*, a main effect of *configuration* was observed [$F(1, 27) = 5.420$, $p = .028$, $\eta^2 = .167$], such that in general, linearly-constructed stimuli elicited higher (more negative) N170 amplitudes than squarely-constructed ones [Linear: $M = -1.48$, $SD = 1.46$; Square: $M = -1.36$, $SD = 1.43$]. This is qualified by an interaction effect of *configuration* $\times$ *stimuli type* [$F(4, 108) = 2.57$, $p = .042$, $\eta^2 = .087$], suggesting that the bilateral N170 amplitudes for some stimuli types were more sensitive to effects of spatial configuration than others. Critically, we observed a significant interaction effect of *configuration* $\times$ *hemisphere* [$F(1,27) = 6.97$, $p = .014$, $\eta^2 = .205$], such that N170 amplitudes for linearly constructed stimuli were more left-lateralized than those for squarely constructed stimuli, thereby replicating Study One's finding that N170 laterality is modulated by spatial configuration (see Figure 10 for topographic maps) [For linear stimuli, LH: $M = -1.74$, $SD = 1.53$, RH: $M = -1.22$, $SD = 1.42$; for square stimuli, LH: $M = -1.53$, $SD = 1.56$, RH: $M = -1.19$, $SD = 1.45$]. Separate ANOVAs performed for each hemisphere revealed that this interaction is mainly motivated by higher (more negative) amplitudes for linear stimuli than for square in the LH [$F(1, 27) = 15.25$, $p = .001$, $\eta^2 = .361$]. In contrast, N170 amplitudes in the RH were not sensitive to spatial configuration [$F(1, 27) = 0.21$, $p = .650$, $\eta^2 = .008$]. Furthermore, the absence of *spatial configuration* $\times$ *stimuli type* $\times$ *hemisphere* interaction indicates that the effects of spatial configuration on N170 lateralization were not further modulated by stimulus category [$F(4, 108) = 1.09$, $p = .367$, $\eta^2 = .039$].

Figure 10. Topographic maps at $t = 141 - 214$ ms corresponding to the N170 time window for linear (left) and square (right) stimuli. Posterior negativity was significantly more left-lateralized for linear stimuli.

Other Significant Effects. The grand ANOVA above also returned a significant main effect of *hemisphere* [$F(1, 27) = 6.081, p = .020, \eta^2 = .184$], indicating that overall, N170 amplitudes were more negative in the LH ($M = -1.63, SD = 1.59$) than in the RH ($M = -1.21, SD = 1.42$). This was qualified by a significant interaction of *stimuli type* $\times$ *hemisphere* [$F(4, 108) = 9.110, p < .001, \eta^2 = .252$], signifying that N170 laterality was modulated by stimulus category, suggestive of some sort of N1 tuning effect. This will be explored in detail in the following section.

5.3.2.2 N1 Tuning Effects

Coarse N1 Tuning. Other than the main effect of *configuration* reported in the grand ANOVA above [$F(1, 27) = 10.96, p = .003, \eta^2 = .289$; linear eliciting more negative N170 amplitudes than square], the repeated measures ANOVA of *configuration* $\times$ *stimuli type* (*words vs. symbols vs. artificial words*) $\times$ *hemisphere* also

returned a significant interaction effect of *stimuli type* $\times$ *hemisphere* [$F(2, 54) = 14.26$, $p < .001$, $\eta p^2 = .346$], demonstrating a coarse N1 tuning effect where N170 amplitudes were significantly more left-lateralized for *words* (LH: $M = -1.82$, $SD = 1.65$; RH: $M = -1.20$, $SD = 1.62$) than for *symbols* (LH: $M = -1.64$, $SD = 1.89$; RH: $M = -1.51$, $SD = 1.67$), and *artificial words* (LH: -1.34 , $SD = 1.80$; RH: $M = 1.09$, $SD = 1.57$). Spatial configuration had no influence over this tuning effect, as indicated by the absence of a *configuration* $\times$ *stimuli type* $\times$ *hemisphere* interaction [$F(2, 54) = 0.946$, $p = .395$, $\eta p^2 = .034$].

Figure 11. Topographic maps at $t = 141 - 214$ ms corresponding to the N170 time window for Words (left) and Symbols (right). The posterior negativity is left-lateralized for Words, while it is bilateral for Symbols ($p < .001$).

While tuning effects were clearly evident in the LH [$F(2, 54) = 3.99$, $p = .024$, $\eta p^2 = .129$], they were not as apparent in the RH. In the LH, *words* had significant higher N170 amplitudes relative to *symbols* and *artificial words*. In contrast, in the RH, the main effect of *stimuli type* was not significant [$F(2, 54) = 1.72$, $p = .188$, $\eta p^2 = .060$],

although the planned comparison between *artificial words* and *symbols* was significant after Bonferroni correction ($p = .015$), suggesting that the RH displayed preferential activity for symbols.

In the ANOVA comparing *nonwords* against *symbols* and *artificial words*, coarse N1 tuning was also observed [$F(2, 54) = 4.73$, $p = .013$, $\eta^2 = .149$], such that *nonwords* (LI: -0.46) elicited significantly more left-lateralized N170 amplitudes than *symbols* (LI: -0.10). However, *artificial words* (LI: -0.255) did not significantly differ from *nonwords*. Further ANOVAs performed for each hemisphere resulted in non-significant tuning effects [$Fs(2, 54) < 2.05$, $ps > .139$], suggesting that the tuning effects observed could not be attributed to selectivity at individual hemispheres, but rather are a result of combined effects of tuning towards characters in the LH, and towards symbols in the RH.

Fine N1 Tuning. In the repeated measures ANOVA of *configuration* $\times$ *stimuli type* (*words* vs. *pseudowords* vs. *nonwords*) $\times$ *hemisphere*, the only significant effects observed were again, a main effect of *hemisphere* [$F(1, 27) = 9.51$, $p = .005$, $\eta^2 = .260$; LH more negative than RH], and an interaction effect of *configuration* $\times$ *hemisphere* [$F(1, 27) = 5.50$, $p = .027$, $\eta^2 = .169$; more left-lateralized for linear stimuli]. The absence of a *stimuli type* $\times$ *hemisphere* interaction suggests that fine N1 tuning effects were not apparent [$F(2, 54) = 2.03$, $p = .142$, $\eta^2 = .070$]. This lack of fine N1 tuning effects cannot be attributed to the unfamiliar configuration in the square stimuli, as the interaction of *configuration* $\times$ *stimuli* $\times$ *hemisphere* was also non-significant [$F(2, 54) = 1.67$, $p = .199$, $\eta^2 = .058$], suggesting that N1 tuning effects were absent regardless

of spatial configuration. The differences in N170 laterality across stimuli types are illustrated in Figure 12 below.

Figure 12. N170 Lateralization Index (LI) across stimuli types. Y-axis plotted in reverse polarity. Negative polarity indicates left-lateralization. Magnitude indicates degree of lateralization. Error bars represent standard errors. Asterisks indicates that the lateralization index is significantly different from 0; * $p < .05$, ** $p < .01$.

5.3.3 Supplementary Analyses

5.3.3.1 P100 (80 – 141 ms)

The overall ANOVA returned a significant main effect of *stimuli* [$F(4, 108) = 5.31, p = .001, \eta^2 = .164$], where P100 amplitudes for artificial words ($M = 0.67, SD = 0.76$), and symbols ($M = 0.62, SD = 0.71$), were significantly higher than that for orthographic stimuli [words: $M = 0.42, SD = 0.72$, pseudowords: $M = 0.34, SD = 0.77$, nonwords: $M = 0.41, SD = 0.83$], demonstrating the earliest signs of print sensitivity. In

addition, a *stimuli x hemisphere* interaction was observed [$F(4, 108) = 2.59, p = .040, \eta^2 = .088$]. However, the nature of the interaction was not in line with the prediction of coarse or fine print tuning effects, as it was mainly driven by weaker P100 amplitudes in the LH for pseudowords, as compared to other stimuli types.

5.3.3.2 P200 (214 – 280 ms)

In the P200 time window, main effects of *stimuli* [$F(4, 108) = 16.50, p < .001, \eta^2 = .379$] and *hemisphere* [$F(1, 27) = 21.57, p < .001, \eta^2 = .444$] were significant. In the former main effect, P200 amplitudes were significantly higher for *artificial words* ($M = 1.24, SD = 1.12$) than for other stimulus types (*words*: $M = 0.31, SD = 0.97$, *pseudowords*: $M = 0.48, SD = 0.90$, *nonwords*: $M = 0.50, SD = 0.83$, *symbols*: $M = 0.66, SD = 0.86$). In the latter main effect, P200 amplitudes in the RH ($M = 0.91, SD = 0.93$) were higher than that in the LH ($M = 0.35, SD = 0.88$).

There was also a significant interaction effect between *stimuli* and *hemisphere* [$F(4, 108) = 4.29, p = .003, \eta^2 = .137$], suggesting that P2 laterality is sensitive to stimulus type. Further analyses revealed that the P2 laterality demonstrates effects of coarse print tuning of *words* vs. *symbols* [$F(2, 54) = 4.66, p = .014, \eta^2 = .147$], where *words* (Lateralization Index (LI): -0.75) elicit more right-lateralized P2 amplitudes than *symbols* (LI: -0.39). However, coarse printing of *characters (nonwords)* vs *symbols* was not significant [$F(2, 54) = 0.40, p = .672, \eta^2 = .015$]. Fine print tuning effects [$F(2, 54) = 4.02, p = .024, \eta^2 = .129$] was also observed, where *words* (LI: -.75) and *pseudowords* (LI: -0.78) elicited more right-lateralized P2 amplitudes than *nonwords* (LI: -0.50), although pairwise comparisons were not significant after Bonferroni correction ($p =$

.061 for *words* vs. *nonwords*; $p = .081$ for *pseudowords* vs. *nonwords*). Differences in P2 laterality are illustrated in Figure 13 below.

Figure 13. Topographic maps at $t = 214 - 280$ ms, corresponding to the P2 time window. Posterior positivity was more significantly more right-lateralized for words than for symbols, along with a trend of more right-lateralization for words and pseudowords than for nonwords.

Further analyses within each hemisphere revealed significant coarse print tuning effects in both hemispheres (LH: [$F(2, 54) = 19.16, p < .001, \eta^2 = .415$]; RH: [$F(2, 54) = 21.42, p < .001, \eta^2 = .442$]), where P2 amplitudes were significantly lower for *words* and *symbols* than for *artificial words*. However, in the LH, there was a further distinction between *words* and *symbols*, such that P2 amplitudes were lower for *words* than for *symbols*. In contrast, P2 amplitudes for *words* and *symbols* in the RH did not differ significantly. Fine print tuning effects were only observed in the LH [$F(2, 54) = 4.24, p = .019, \eta^2 = .136$], characterized by lower P2 amplitudes for *words* than for *nonwords*. No significant differences were found for *words* vs. *pseudowords*, and *pseudowords* vs. *nonwords* comparisons after Bonferroni adjustment. There were no significant fine print tuning effects in the RH [$F(2, 54) = 2.04, p = .140, \eta^2 = .070$]. A summary of primary and supplementary ERP analyses is provided in Table 7 below.

Table 7. Summary of significant main (N170) and supplementary (P100 & P200) ERP analysis findings. - indicates that the effect was not statistically significant.

Effect	P100	N170	P200
Spatial Configuration	-	More left-lateralized for Linear than for Square; effects prominent in LH, where Linear > Square	-
Coarse Tuning:			
Words vs. Symbols	Words < Symbols bilaterally	More left-lateralized for Words than for Symbols; LH: Words > Symbols; RH: Symbols > Words	Symbols more left-lateralized than Words; effects prominent in LH
Characters vs. Symbols	Characters < Symbols bilaterally	More left-lateralized for Characters than for Symbols; tuning effects not significant in individual hemispheres	-
Fine Tuning:			
Words vs. Pseudowords	-	-	-
Words vs. Nonwords	-	-	Nonwords more left-lateralized than Words; effects prominent in LH

5.3.4 Cognitive Correlates of N1 Tuning

The cognitive tasks had good within-construct correlations, where performance in the two tasks measuring phonological skills, Spelling of Sounds and Sound Blending, were positively correlated with each other ($r = .677, p < .001$). This was the same for the two tasks measuring visuospatial abilities, Spatial Relations and Picture Recognition ($r = .510, p < .01$). At the same time, between-construct correlations were low (all r s falling between $-.68$ and $.173, ps > .409$), suggesting that the two groups of tasks (phonological vs. visuospatial) were assessing distinct sets of skills.

5.3.4.1 Coarse N1 Tuning

Tuning towards *words* over *symbols* and *artificial words* were not significantly correlated with phonological nor visuospatial skills ($ps > .05$). However, tuning towards *characters (nonwords)* over *artificial words* was associated with visuospatial skills, such that subjects with stronger visuospatial abilities had more left-lateralized N170 amplitudes for nonwords than for artificial words (Spatial Relations task: $r = -.536, p < .01$; Picture Recognition task: $r = -.381, p = .060$). This correlation was not observed when the symbols were familiar to the subjects, as indicated by the absence of significant correlations for the *Nonwords > Symbols* tuning. This suggests that the N1 coarse tuning effect of increased left-lateralization for letters vs. unfamiliar symbols is related to visuospatial processing demands.

5.3.4.2 Fine N1 Tuning

Phonological skills, specifically sound blending abilities, were associated with N170 lateralization differences between *pseudowords* and *words*, such that subjects with

stronger phonological skills had more left-lateralized N170 amplitudes for *pseudowords* than for *words* (Sound Blending: $r = .443$, $p < .05$; Spelling of Sounds: $r = .357$, $p = .079$), suggesting that the increase in left-lateralization for pseudowords may be related to demands on phonological processing.

Table 8. Pearson's correlations between coarse and fine N1 tuning effects and performance in cognitive tasks measuring phonological and visuospatial abilities.

	Spelling of Sounds	Sound Blending	Spatial Relations	Picture Recognition
COARSE N1 TUNING				
Words > Symbols	-.166	-.078	-.006	.094
Words > Art. Wds	-.047	-.170	-.344	-.097
Nonwords > Symbols	-.098	-.113	-.339	-.275
Nonwords > Art. Wds	.008	.083	-.536**	-.381 [#]
FINE N1 TUNING				
Words > Pseudowords	.357	.443*	.064	-.180
Words > Nonwords	-.048	.045	.335	.359

Note. [#] $p < .06$, * $p < .05$, ** $p < .01$; Art Wds – artificial words.

5.4 Discussion

Study Two replicated Study One's findings on spatial configuration's influence over N170 lateralization, where linearly-constructed stimuli elicited significantly more left-lateralized N170 amplitudes than those that were squarely-constructed. With regards to print tuning effects, coarse N1 print tuning effects were, with more left-lateralized activity for words/characters than for symbols. This coarse print tuning effect is likely attributed to both selectivity for words in the LH, and selectivity for symbols in the RH. Fine print tuning effects were not observed in the N170 window, but did however emerge later in the P200, in which both coarse and fine print tuning effects were observed. The earliest signs of print sensitivity emerged in the P100, where words/characters elicited lower activity than symbols and artificial words. Correlations between cognitive tasks and print tuning effects suggest that at least some aspects of coarse N1 tuning effects are related to visuospatial processing, while fine N1 tuning effects, in particular the contrast between pseudowords and words, are related to phonological processing. Each of these findings will be discussed at length.

5.4.1 Effects of Spatial Configuration on N170 Lateralization

In the three early ERP components studied, effects of spatial configuration were only evident in the N170, which has been source-localized to the occipitotemporal region. The effects of spatial configuration on N170 lateralization were robust, observed regardless of stimulus type. Specifically, linearly-constructed stimuli elicited more left-lateralized response than squarely-constructed stimuli, and this effect was mainly driven by heightened activity for linear stimuli in the LH. Crucially, the preference for linear stimuli in the LH did not seem to arise from greater language-related processing when

orthographic stimuli is in a familiar configuration (linear for English), as the preference was not influenced by stimulus type. Therefore, a more plausible explanation is that the LH has a general visuoperceptual preference for linear constructions. Linear constructions in which sub-units are arranged in a serial fashion may place larger demands on sequential/part processing and analysis, which have been proposed to be left-lateralized (e.g., Patterson and Bradshaw, 1975; Robertson and Lamb, 1991; Tzeng et al., 1979). Lesion studies informed us that patients with a left OT damage tend to have impairments in reading (often referred to as “pure alexia”), which are more pronounced as word length increases (Behrmann, Plaut, and Nelson, 1998). The word length effect commonly seen in alexia is thought to be a consequence of reduced visual span (Starrfelt, Habekost, and Leff, 2009), suggesting that the left OT is critically involved in the processing of sequences. In contrast, square constructions, due to their compact structure, may recruit sequence processing to a lesser extent, thereby involving the LH to a smaller degree. This explanation fits well with previous reports that single Japanese Kanji characters have an LVF/RH advantage, while compound Kanji words have an RVF/LH advantage (e.g., Hatta, 1978, Kess & Miyamoto, 2000).

The present findings thus clearly demonstrate that N170 lateralization is sensitive to visual spatial processing demands. In relation to existing literature, differences of spatial configuration may be able to partly explain the observation that N170 amplitudes for logographic scripts tend to be less left-lateralized than for alphabetic scripts (Wang and Maurer, 2017; Xue et al., 2008), such that the linear construction in alphabetic languages induce greater LH N170 negativity than the square construction in logographic languages.

5.4.2 Print Tuning Effects in N170 Lateralization

Consistent with the literature on coarse N1 tuning for print, words and nonwords alike elicited more left-lateralized N170 activity than symbols (Brem et al., 2005, 2013; Maurer and McCandliss, 2008; Maurer et al., 2005, 2011, 2008; Wang and Maurer, 2017; Wong et al., 2005). Orthographic stimuli (words, pseudowords, nonwords) all elicited significantly left-lateralized N170s, while it was bilateral for symbols and artificial words, suggesting that the left-lateralization reflects visuoperceptual expertise for English letters. It was further found that this coarse print tuning effect was attributed to both heightened activity for orthographic stimuli in the LH, and for symbols in the RH. While previous studies on N1 tuning did not always report tuning effects within individual hemispheres, these findings are consistent with at least two earlier ERP studies which reported enhanced RH N170 amplitudes for symbols strings relative to letter strings (Appelbaum et al., 2009; Bentin et al., 1999), and an fMRI study which found greater selectivity for words over symbols (the same type of alphanumeric symbols used in our study) in the left anterior fusiform gyrus, whereas right hemisphere regions showed greater selectivity for symbols over words (Carreiras et al., 2014).

On the flip side, the lateralization index between nonwords and artificial words did not differ significantly. Some studies in the literature reported less robust effects of coarse N1 tuning when the control stimuli were matched with orthographic stimuli on lower-level visual features, such as with the use of foreign letter strings or false fonts rather than geometric shapes (e.g., Xue, Jiang, Chen, & Dong, 2008; Zhao et al., 2014). As the artificial words used in this study are created with characters in a real-world script and are visually complex, the coarse print tuning effect may have been reduced.

In sum, analysis of coarse print tuning effects revealed a general expertise effect for familiar orthographic stimuli, and again demonstrated that N170 lateralization may be reflective of visuoperceptual processing demands, in the sense that when the control stimulus (artificial words) matches the orthographic stimuli on lower-level visual features, the N170 lateralization patterns for the two do not differ significantly.

In contrast with the coarse print tuning effects, fine print tuning effects were not apparent in the N170 time window. In the literature, fine N1 print tuning effects have been elusive at best. Among those that observed fine print tuning effects, some found words and pseudowords elicit more left-lateralized N170 amplitudes than unpronounceable letter strings (e.g., Coch & Mitra, 2010; McCandliss, Posner, & Givon, 1997), or at an even finer-grain level, that words produce more left-lateralized N170 activity than pseudowords (e.g., Maurer, Brandeis, et al., 2005), and yet some others reported the reverse, where pseudowords elicited more left-lateralized responses than words (e.g., Kim and Strakova, 2012). On the other hand, a number of studies found no lexical effects at N1 (e.g., Bentin et al, 1999; Eberhard-Moscicka et al., 2015; Kast, Elmer, Jancke & Meyer, 2010). The present findings add on to the latter group of studies, and support the notion that the left-lateralization of the N170 component is related to general perceptual expertise for letters, and is not susceptible to lexicality or orthographic regularity effects.

5.4.3 Cognitive Correlates of Print Tuning

The coarse N1 tuning effect of characters > artificial words and the fine N1 tuning effect of pseudowords > words, while not significant, were associated with

subjects' visuospatial skills and phonological skills respectively. Subjects with better visuospatial abilities demonstrated stronger coarse print tuning effects, suggesting that the enhanced left-lateralization for letter strings relative to a well-matched visual control may stem from greater sensitivity to visuoperceptual features. In contrast, the absence of significant correlations between the tuning effect of words/pseudowords > artificial words and visuospatial skills possibly indicates that the greater left-lateralization for words and pseudowords than for other letter-like stimuli is less reliant on a visuoperceptual process, and may reflect the special status of well-formed letter strings. At the same time, subjects with better phonological skills demonstrated stronger fine print tuning effects, with more left-lateralized activity for pseudowords than for words. It is thus likely that the enhanced left-lateralization for pseudowords relative to words is related to additional demands on phonological processing, since the reading of pseudowords requires a greater reliance on grapheme-phoneme mapping than the reading of real words. Lastly, the print tuning of words > symbols, while significant, did not correlate with the performance of any of the tasks administered. This signifies that in proficient adult readers, expertise for words is salient and not affected by individual variability in visuospatial or phonological abilities.

The strength of print tuning effects at an individual level have been associated with reading skills in children. In alphabetic readers, Maurer et al. (2007) found that the coarse print tuning effect of words > symbols correlated with the reading speed of second graders, and dyslexics were characterized by the absence of print tuning. A later study found that children with lower phonological awareness displayed weaker print tuning effects (Sacchi and Laszlo, 2016), highlighting the role of phonological processing in driving left-lateralization towards print. In Chinese reading, coarse N1

tuning was also found to be an index of reading fluency (Tong et al., 2016), although the degree of tuning is thought to be driven by orthographic, rather than phonological, processing. In adults, the relationship between print tuning and reading abilities was often demonstrated in dyslexia studies, where dyslexics have a marked absence of print tuning (Mahe et al., 2012; Setten et al., 2018), but studies investigating print tuning variations within normal readers are scarce.

This study thus fills a gap in the literature by finding strong word > symbol tuning in normal adult readers, which is not influenced by individual differences in phonological and visuospatial abilities. However, the expertise for letter strings (and not words) over well-matched visual control are related to visuoperceptual skills, while the enhanced left-lateralization for pseudowords over words tend to be more salient in individuals with stronger phonological skills. Interestingly, these two tuning effects - coarse N1 tuning when well-matched visual control is used, and fine N1 tuning effects, which did not emerge significant in our study, have arguably the most divergent findings amongst the N1 tuning literature. It is thus speculated that individual differences in visuospatial and phonological abilities may potentially account for some of the discrepancies in the existing literature, as population tuning effects may vary with subjects' overall phonological and visuospatial abilities.

5.4.4. Earliest Signs of Print Sensitivity – The P100 Component

For completeness, supplementary analyses on P100 and P200 components were performed to study possible early print tuning effects outside of the N170. There were reduced P100 amplitudes bilaterally for words/characters relative to symbols and

artificial words. As the P1 is generally thought to reflect early attention allocation processes in the extrastriate cortex (Hillyard and Anllo-Vento, 1998), the lower P1 amplitudes for orthographic stimuli are indicative of lower attentional demands, again reflecting general visuoperceptual expertise for letters. However, print tuning effects in the P1 time window have not been consistently reported in the literature (as discussed in Wang and Maurer, 2017). It has been hypothesized that print tuning effects at P1 may arise from poorly-matched control stimuli, such as the use of geometric shapes which are visuoperceptually distinct from letters, as studies utilizing false fonts (which are more visually similar to orthographic stimuli) tend to report absence of P1 print tuning effects (e.g., Eberhard-Moscicka et al., 2015; Xue et al., 2008). However, the control stimuli in this study are more alike to false fonts rather geometric shapes, and print tuning effects were still observed at P1. The present findings thus likely reflect the lower attentional costs associated with the processing of familiar letter strings. Such effects may be more salient with the adoption of a blocked design, where subjects have strong expectations on the stimulus class of the subsequent trial, relative to randomized trial presentation.

5.4.5 Print Tuning Effects in The P200 Component

Robust print tuning effects were observed in the P200 time window. The nature of the print tuning was aligned with effects of both coarse and fine print tuning, with some effects observed bilaterally, and some only in the LH. Bilateral P200 differentiated unfamiliar symbols (artificial words) from words, such that the former elicited greater P200 amplitudes. P200 amplitudes in the LH seemed to exhibit greater sensitivity to stimulus category, as further distinctions were made between words and symbols, and between words and characters, indicative of finer print tuning processes.

As the P200 component has not received much attention in the visual word processing literature, interpretations can only be made within the context of the limited existing works. The visual P2 component, typically generated in parieto-occipital regions (Freunberger, Klimesch, Doppelmayr, & Holler, 2007), is thought to index working memory function (Lefebvre, Marchand, Eskes, & Connolly, 2005; Taylor, Smith, & Iron, 1990; Wolach & Pratt 2001), in particular encoding (e.g. Dunn, Dunn, Languis, & Andrews, 1998). Previous studies seem to suggest that P2 amplitudes are larger for stimuli that are difficult to encode, such that consonant strings elicited larger P2 amplitudes than words (McCandliss et al., 1997). A recent study that investigated word-likeness effects in the P2 component found that false fonts elicited larger P2 amplitudes than letter strings, and also larger P2s for letter strings than for words (Coch and Meade, 2016), although the latter effect was only seen in children but not in adults. Relatedly, reduction in P2 activity sourced from occipitotemporal cortex has also been reported in tasks involving stimulus repetition, and the magnitude of reduction was found to be modulated by stimulus familiarity (Fiebach, Gruber and Supp, 2005). Considering these previous works, the present findings appear to demonstrate the sensitivity of the P2 to encoding difficulty, where largest difficulty was encountered for unfamiliar symbol strings, and words were encoded with relative ease. An alternative but not incompatible explanation is that with the adoption of a one-back (repetition detection) task, differential effects of repetition (which took place for half the trials) may have led to larger reduction of P2 amplitudes for familiar stimuli (words) than for unfamiliar stimuli (artificial words).

The effects of stimulus familiarity on P2 reduction were greater in the LH, contrasting with studies on face processing which found stronger stimulus repetition

effects in the RH (e.g., Henson, Shallice, and Dolan, 2002). This suggests that the interhemispheric differences in P2 reduction to familiar stimulus is modulated by stimulus category, and exhibits typical LH-dominant effects for words/characters, and RH-dominant effects for faces. It is further demonstrated that the LH makes distinction between familiar alphanumeric symbols and unfamiliar artificial words, indicating that the familiarity effects in LH are not limited to letter strings.

Lastly, it should be acknowledged that the P200 has also been implicated in phonological (e.g., Bann & Herdman, 2016) and semantic processes (e.g., Moreno, Federmeier, & Kutas, 2002), and there may be other possible interpretations for the above findings. As the functional sensitivity of the P200 component lies outside the scope of the present study, I keep to providing a simplistic explanation in this thesis and recommend future investigations on this matter.

5.4.6 Limitations and Summary

To keep the trial history across stimulus blocks identical, efforts were made to closely match the different stimulus types in terms of number of building units in each stimulus type and positions in which each building unit could occur. This inevitably meant that certain sacrifices had to be made. For instance, word frequency could not be controlled for. Word frequency has been found to exert influence on both the amplitude and the latency of the N170, such that low frequency words elicit larger and delayed N170 as compared to high frequency words (Hauk & Pulvermüller, 2004; Wang, Kuo, & Cheng, 2011). Hence, N170 amplitudes for words may might have been lower if only high frequency words were used, and consequently there might have been significant

differences between the N170 activity/lateralization for words and pseudowords. However, word frequency effects may be dampened when repetition is involved, such as in a one-back task in the present study (Wang, Kuo, & Cheng, 2011). It is thus unlikely that word frequency had significant influence over the findings in this study.

All in all, findings from Study Two established the early electrophysiological effects of visual word processing as follows: At the P100 time window, bilateral positivity was lower for orthographic stimuli than for non-orthographic stimuli, a sign of reduced attentional demands for familiar orthographic stimuli regardless of lexical status. Next, at the N170 time window, lateralization effects were observed. While the P100 made a distinction between orthographic and non-orthographic stimuli in terms of amplitudes, the N170 was differentially lateralized for the two. The N170 was left-lateralized for orthographic stimuli, and bilateralized for non-orthographic stimuli. The differences in lateralization patterns seemed to be a combined outcome of general print selectivity in the LH, and a preference for symbols in the RH. The second lateralization effect observed at the N170 time window stemmed from spatial configurational differences, in which linear stimuli elicited more left-lateralized N170s than square stimuli. This effect was mainly driven by greater activity for linear stimuli in the LH. Finally, at the P200 time window, effects of lexicality and orthographic regularity emerged, such that the LH P200 was smaller for words than for nonwords, while pseudowords did not differ from the two.

Chapter 6:

General Discussion

This thesis set out to achieve a clearer understanding of how N170 laterality for visual word processing may be differentially shaped by visuoperceptual and phonological processing demands, and in turn understand what the N170 potentially indexes in visual word processing, other than familiarity and general visual expertise. This was achieved by varying the phonological and visuoperceptual processing demands systemically in the two studies of this thesis. Phonological demands were manipulated by varying orthographic depth in Study One, and by contrasting different word types (words, pseudowords, nonwords) in Study Two. Visuoperceptual processing demands varied with the manipulation of spatial configuration in both Study One and Two, and with the inclusion of familiar symbols and unfamiliar letter-like artificial words in Study Two.

6.1 Summary of Findings

In Study One, it was found that an orthography of a square configuration placed more demands on visuospatial processing, such that subjects with stronger visuospatial skills achieved better word learning performance, especially in the square and deep orthography. This is accompanied by the finding that bilateral N170 activity were elicited for square orthographies, as opposed to linear orthographies which elicit left-lateralized activity. Such effects were observed when subjects viewed the stimuli as unfamiliar symbol strings (pre-training), and persisted when the symbols were no longer

novel (post-training; the general increase in N170 amplitudes demonstrated subjects' familiarity and initial expertise for the stimuli). This unprecedented finding led to further investigations in Study Two, questioning if such an effect would also be observed when the stimulus is of high familiarity. The same pattern of lateralization differences emerged. Study Two also replicated coarse N1 print tuning effects reported in the literature, where N170 activity was left-lateralized for orthographic stimuli, but bilateralized for non-orthographic stimuli. However, fine print tuning effects did not emerge, as no further distinctions were made among the orthographic stimuli. Crucially, most of the significant effects observed were mainly sourced from the LH's selectivity towards linear stimuli and orthographic stimuli, accompanied with the RH's preferential activity for symbols. Through the investigation of cognitive correlates of print tuning effects, it was uncovered that some aspects of coarse print tuning effect are related to visuospatial processing, while fine print tuning effects are more dependent on phonological processes.

6.2 The Special Status of Linear Orthographic Strings

The primary findings in this thesis showed a general preference for orthographic stimuli in the LH, with no further distinctions based on meaningfulness or orthographic regularity. Considering the N170's primary role as an index of perceptual expertise, there is a need to address what is special about orthographic stimuli perceptually, as compared to symbols. In a behavioral experiment done by Tydgat and Grainger (2009), it was found that when presented with a 5-character string, subjects had the highest accuracy for the first, central, and final positions for consonant strings and numbers. In contrast, when the string was made of alphanumeric symbols and geometric shapes, the

accuracy was highest in the center, and decreased outwards. The reduced crowding effect for consonant strings and numbers suggest that humans have learnt to dedicate greater attentional resources to the ends of a string in order to process the letters/numbers at the two ends, as well as to encode the relative positions of letters/numbers within a string. Such processing is not demanded for symbols and shapes which normally do not occur in a string, and even if they do, they are rarely meaningful. It thus seems at the encoding stage, letters and symbols differ in that the former demands more attention to other entities in the string. This letter advantage is described in the theoretical framework proposed by Grainger, Dufau and Ziegler (2016), where reading critically involves the parallel processing of letter strings by gaze-centered letter detectors that encode letter identity and letter location simultaneously. Crucially, the framework made reference to the importance of the dorsal stream in directing spatial attention for the successful identification of letters and their orders within a word. This ties in nicely with Vogel's (2014) argument that the left occipitotemporal region is particularly useful for reading due to its sensitivity to visual complexity and "groupability" of the stimulus, and that these functional characteristics are driven by its preferential connectivity with the dorsal attention network related to feature and spatial attention.

Intriguingly, Grainger's paper highlighted the importance of horizontal arrangement of letters which the visual system has learned to adapt to (for alphabetic script readers), citing an earlier study which found that the letter advantage in reduced crowding effects was not observed when the string was arranged vertically (Vejnovic and Zdravkovic, 2015). The simultaneous processing of orthographic stimuli is thus interrupted when it is not in a linear and horizontal arrangement. Fittingly, in this thesis, the LH N170 was mainly modulated by two parameters: linearity of the stimuli, and

orthographic status. First, the LH N170 was larger for linear relative to square stimuli. Second, the LH N170 was larger for orthographic stimuli than for non-orthographic stimuli. Considering the unique perceptual characteristics of orthographic strings discussed above, the findings in this thesis suggest that the LH N170 increases when the visual stimulus demands greater simultaneous processing of horizontally-arranged strings. This fits well with the observation that lesions to the LH occipitotemporal region commonly result in alexia, a reading deficit characterized by effortful letter-by-letter reading due to the general inability to process visual stimuli simultaneously (Starrfelt, Habekost, & Leff, 2009). The greater LH N170 amplitudes for linear and orthographic stimuli observed in this thesis can thus be explained as follows: 1) As the square stimuli did not resemble horizontal strings, LH N170 amplitudes were reduced. 2) Orthographic stimuli place higher demands on the simultaneous processing of multiple entities within the string, as they are potentially meaningful. This in turn activates the left hemisphere more strongly. This interpretation of LH N170 activity is compatible with other theories from the Visuoperceptual perspective, such as the LH bias for linear processing, and the LH preference for high spatial frequency information, because the simultaneous processing of horizontal strings would require more linear processing, as well as greater attention to high spatial frequency, detailed information to entities within the string.

The proposal that LH N170 reflects simultaneous processing of horizontal strings may also explain some of the findings and discrepancies in the word N170 literature. For example, the observation that N170 for single letters tend to be bilateral while the N170 for words tend to be left-lateralized for alphabetic languages can be explained by the need for simultaneous processing of multiple letters in words, but not in single letters. Cross-linguistic differences between alphabetic and logographic

languages in N170 lateralization may also be explained in terms of greater demands for simultaneous processing of horizontally-arranged letter strings in the former. Interestingly, it has been speculated that the contradictory findings on N170 lateralization for logographic languages may be partly attributed to the use of single characters vs. compound words, such that it tends to be bilateral for the former and left-lateralized for the latter (Niermeyer, Miller, Tamaoki, Wiggling, and Stevens, 2018), resembling the lateralization effects for alphabetic scripts. It thus seems plausible that compound word processing in logographic scripts may be more left-lateralized than single character processing because compound words would require greater simultaneous processing of the horizontally-arranged characters within the word.

6.3 The Importance of Orthographic Regularity

In Study Two, fine N1 print tuning effects did not emerge to be significant when N170 amplitudes in both left and right hemispheres were considered in the ANOVA. As a result, there was no reason to perform further analyses within individual hemispheres. Given the observation that the LH N170 amplitudes, rather than N170 lateralization, may be a better index of orthographic processing, retrospective analyses were performed to explore fine N1 print tuning effects within each hemisphere. Fine N1 print tuning effects then emerged only in the left hemisphere, but not in the right. The effect is characterized by significantly greater N170 amplitudes for words ($M = -1.82$) and pseudowords ($M = -1.88$) than for nonwords ($M = -1.61$). These results suggest that orthographic regularity modulates LH N170 activity. Furthermore, the correlation between coarse N1 print tuning effects and visuospatial skills only emerged when the orthographic stimulus was orthographically illegal (nonwords), but not when it was

orthographically regular (words and pseudowords), again implicating the role of orthographic regularity in driving a left-lateralized N170 response. It thus suggests that the LH also concerns with orthographic regularity, other than simultaneous processing and linearity.

While the greater LH activity for orthographically regular, and thus pronounceable, stimuli may be interpreted as an evidence in support of the Phonological Mapping Account, it is not incompatible with the Visuo-perceptual Account, and the current proposal that LH N170 represents the simultaneous processing of strings. It has been posited that the left occipitotemporal region becomes tuned to the orthographic rules within a language due to extensive exposure to letters that appear as a group regularly (Vogel, 2012), a consequence of domain-general statistical learning mechanism. The attentional capture is thus greater for orthographic strings that conforms to the statistical regularities within a given script. As discussed earlier, letter strings gain special status in capturing attention and demand greater simultaneous processing due to the potentiality to bear meaning. It is thus not unreasonable that for greater processing efficiency, letter combinations that do not conform to statistical rules, thus having less potentiality to bear meaning, would demand less attention and encoding effort. As a result, orthographically illegal letter strings are less robustly encoded by the left hemisphere. This effect is then manifested as reduced LH N170 amplitudes for nonwords relative to words and pseudowords, a form of fine print tuning effect.

6.4 The Role of Phonology Mapping

Up to this point, the findings in this thesis have been explained mostly from a Visuo-perceptual perspective, primarily because most of the effects observed were related to visuospatial (linear vs. square configuration) and perceptual (orthographic vs. other visual controls) differences. What role does phonological mapping assume then? To answer this question, let us first consider the lateralization effects observed in this thesis which could have been related to phonological processing. In Study One, the training-related changes in N170 lateralization, while not significant, tended to be influenced by the orthographic transparency of the script learnt. The pattern of changes in N170 lateralization concurred with previous findings that orthographically transparent scripts would have a more left-lateralized response than orthographically opaque scripts. As subjects across different orthography conditions went through identical training, such differences in lateralization changes, although slightly underwhelming, can be solely attributed to differences in phonology mapping. In Study Two, it was also found that fine N1 print tuning effects may be weakly related to phonological skills, suggesting that expertise in phonological processing can translate into greater visual expertise for pronounceable but non-meaningful letter strings, although the directionality of the relationship was not tested in this study. Retrospective analyses also revealed that LH N170 was larger for well-formed and pronounceable orthographic strings (words and pseudowords) than for nonsense strings (nonwords).

Perhaps, one important point to consider is how effects that are seemingly related to phonological processing may be explained with visuo-perceptual processing. In the literature view, it was mentioned that the Visuo-perceptual Account also predicts that orthographically transparent scripts would elicit more left-lateralized N170 activity than

orthographically opaque scripts. This is due to the greater emphasis placed on individual letter identities in orthographically transparent scripts, thereby requiring more detailed processing of high spatial frequency information. In the above section, the LH preference for orthographically regular stimuli was also explained in terms of greater simultaneous processing for potentially meaningful stimuli via a domain general statistical learning mechanism. What is considered orthographically regular then? This is where phonological mapping plays a critical role. Unlike in logographic scripts where radicals are often confined to certain positions within the character, letters in alphabetic script can occur almost in any position within the letter string. As such, individual letter positions within a string do not provide sufficient information for one to determine whether the string is an orthographically regular construction or not. Orthographic regularity in alphabetic scripts is thus dependent on subword combinatorial orthographic regularity (SCORE; Mano, 2016), where building blocks of words are chunks of letters frequently occurring together rather than individual letters. Given the close, perhaps even inseparable, relationship between orthography and phonology in alphabetic scripts, the establishment of what these chunks are may be shaped by syllabic boundaries, thus implicating the role of phonology mapping. Specifically, the close relationship between orthography and phonology in alphabetic scripts means that orthographic regularity is strongly tied to pronounceability. In other words, whether a cluster of letters can be mapped onto a legal speech sound or syllable serves to determine if the cluster of letters is orthographically regular. For example, we can make the judgement that “procask” could be an English word but not “pocasrk” by considering if the letter clusters within the words correspond to English syllables - the letter clusters “pro” and “cask” map onto single syllables in English, but the letter cluster “casrk” does not map onto a single English syllable. The mapping of phonology thus assists in deciding if a letter string is

orthographically regular, but it is not essential. Without phonological mapping, we can still make the decision that “casrk” is orthographically irregular in English, based on the observation of letter combination rules among English words. In this view, LH N170 is primarily modulated by orthographic regularity, with phonological mapping assuming a backseat role of determining what should be considered orthographic regular in alphabetic scripts.

Support for the notion that LH N170 is modulated by orthographic regularity rather than phonological mapping processes comes from studies on logographic scripts where the relationship between orthography and phonology is largely arbitrary. In Chinese visual word processing, LH N170 activity was found to be related to radical position, such that pseudowords with radicals in legal positions elicit N170 amplitudes of similar magnitudes to real words. In contrast, for nonwords in which radicals occur in illegal positions, the left hemisphere N170 amplitude is significantly reduced (Lin et al., 2011). As pseudowords in Chinese are not pronounceable, the greater left hemisphere activity for pseudowords than for nonwords can only be attributed to orthographic regularity, and not phonological processes. Other studies in the literature have also postulated that phonological representations are not activated until the N320 time window (e.g., Bentin et al., 1999; Simon et al., 2004; Araújo et al., 2015).

Considering the above findings, I reiterate the position that N170 lateralization, in particular LH N170 activity, may not reflect active phonological processes during the N170 time window (i.e. letter-to-sound conversions), and instead primarily indexes orthographic processing. However, N170 lateralization may be influenced by

orthographic transparency and phonological processes by virtue of an offline, long-term process of building orthographic regularity knowledge. While the LH N170 encodes orthographic regularity script-invariantly, determinants of orthographic regularity may differ across alphabetic and logographic scripts. Specifically, orthographic regularity in alphabetic scripts may be partly determined by syllabic boundaries and syllabic construction rules (e.g., certain phoneme pairs cannot occur together), while orthographic regularity in logographic scripts are largely dependent on radical positions. On top of these stimulus-related factors, individual differences in related cognitive skills (i.e. visuospatial skills and phonological skills) also play a minor role in shaping N170 laterality in print processing, as suggested by Study Two findings. The proposed relationships between these factors are illustrated in Figure 14.

Figure 14. Proposed model of determinants of N170 lateralization in visual word processing based on findings in this thesis. Visual-related factors are boxed in blue and phonology-related factors are boxed in green. The model shows that N170 lateralization is mainly influenced by stimulus-level visuoperceptual factors, with phonological mapping playing an indirect role via shaping orthographic regularity. Individual cognitive factors i.e. visuospatial skills and phonological skills also contribute towards N170 lateralization as these skills critically interact with the stimulus factors.

The factors that contribute to N170 lateralization in visual word processing are summarized in Figure 14. This model puts forth that N170 lateralization is primarily influenced by visuoperceptual factors (i.e. spatial configuration and orthographic regularity) likely via a domain-general visual processing mechanism, in which the left hemisphere is specialized for linear and parallel processing of visual stimuli. Phonological mapping is proposed to influence N170 lateralization indirectly via the shaping of orthographic regularity through syllabic boundaries and syllabic construction rules. The cognitive skills related to the abovementioned stimulus-level visuoperceptual and phonological mapping factors, i.e. visuospatial skills and phonological skills respectively, are thus also expected to play a role in shaping N170 lateralization. Importantly, supplementary analyses of the P100 and P200 components informed us that the N170 component marks the start of lateralization effects for orthographic stimuli, as no lateralization effects were observed in the P100 component. Furthermore, there seem to be carry-over effects in the P200 component, in that stimuli that elicited greater left-lateralized N170s went on to elicit more right-lateralized P200s. This suggests that factors that shape N170 lateralization in visual word processing could also shape the lateralization of later ERP components that are prominent in visual word processing. In other words, the proposed model may be extended to account for factors that contribute to hemispheric lateralization in visual word processing in general. This needs to be investigated with further analysis of a greater range of ERP components.

6.5 Reconsidering the Past and Looking to the Future

In light of the proposed alternative role of phonological mapping, let us reconsider some of the word N170 effects in the literature which were not explored in this thesis. First, the relationship between N170 print tuning effects and phonological

skills reported in the literature may be driven by a poorer sense of orthographic regularity in individuals with lower phonological skills. Moreover, tests designed to assess phonological skills often require subjects to perform grapheme-phoneme conversions, tapping on both orthographic and phonological knowledge. This means that the weaker N170 print tuning effects in struggling readers and/or individuals with poorer phonological skills may be driven by lower orthographic awareness rather than phonological awareness. This needs to be verified by investigating the relationship between N170 print tuning effects and performance in a task which primarily taps on orthographic awareness e.g., lexical decision task. Second, as pointed out in the literature review, left-lateralization of the N170 does not seem to occur together with the development of phonological skills or initial reading experience, as there have been reports showing that children as old as twelve years old still elicit a bilateralized N170. The late emergence of the left-lateralization for print could suggest that a high level of abstract orthographic regularity knowledge, rather than phonological awareness or print knowledge, is required for left-lateralization to occur. Accordingly, the onset of left-lateralization may be independent of knowledge of grapheme-phoneme conversion rules, which are acquired earlier. The relationship between N170 left-lateralization and orthographic/phonological awareness can be verified via various means e.g., tracking the development of phonological awareness, orthographic awareness, and N170 laterality, or measuring pre- and post-training N170 laterality for phonologically-trained and orthographically-trained children. Third, the literature has shown that in dyslexic individuals who typically have weaker N1 print tuning effects, the N170 to orthographic stimuli can increase after phonologically-based interventions (Okumura, Kita, & Inagaki, 2017). The stronger print tuning effects post-intervention may be due to the increase in orthographic knowledge, a by-product of phonologically-based interventions.

Thus, there is a need to investigate if an intervention program that highlights orthographic regularity would be more successful in enhancing N1 print tuning effects, and more critically, if such an intervention program would result in greater gains in reading performance as a result of enhanced N1 print tuning effects.

Granted, the studies in this thesis are not without limitations, which have been discussed in their individual chapters. The proposal that LH N170 reflects primarily visuoperceptual processing was made based on the findings observed within the realms of the two studies conducted. Without a doubt, further and more direct forms of testing are warranted to verify if the proposal captures the functional significance of the N170 in visual word processing accurately and precisely. For a start, it needs to be directly tested if modifying word length in logographic scripts would have an effect over LH N170 activity, such that compound words elicit greater LH N170 than single-character words, supporting the notion the LH N170 would be greater for horizontally-arranged, multi-character stimuli. Relatedly, because most scripts in the world feature a horizontal writing direction, it should be verified whether the LH preference for horizontal strings is a pre-existing hemispheric specialty or is developed with language experience. For that, a study exploring how literates and illiterates process visual stimuli of different spatial configurations and levels of wordlikeness can be conducted. If results show a LH preference for a horizontal arrangement regardless of literacy, it would be suggestive of pre-existing hemispheric differences. In contrast, if this LH preference develops with literacy, it may then suggest that the LH occipitotemporal region becomes specialized for horizontal strings due to its closer proximity (relative to its right homologue) to the left hemisphere language regions in the brain (e.g., left hemisphere perisylvian area).

In terms of methodology, the employment of fMRI-EEG technique would also be helpful in accurately identifying the source(s) of the N170 signal in visual processing. As mentioned earlier in this thesis, recent fMRI evidence points to the functional segregation of the left occipitotemporal cortex in reading (Seghier & Price, 2011; Lerma-Usabiaga, Carreiras, & Paz-Alonso, 2018), with a posterior region that is maximally activated for perceptual contrasts, and an anterior region that is maximally activated for lexical contrasts. Discerning if the N170 is sourced from the posterior or anterior portion, or both, would be critical in verifying the processing stage captured in the N170 time window. In addition, both studies in this thesis reported the data from four occipitotemporal electrodes. This approach of preselecting electrodes or electrode clusters is common in ERP studies especially when there is only one ERP component of interest and/or the electrode locations where the signal is maximally observed are well-defined in the literature. Further work adopting whole-brain EEG analysis approaches (e.g., TANOVA analysis, microstate analysis) can provide a more comprehensive understanding of the time-course of visual word processing.

6.6 Conclusion

All in all, the two studies in this thesis together show that N170 lateralization effects in visual word processing is mainly driven by the left hemisphere N170's sensitivity to orthographic regularity and linearity/horizontality of the visual stimulus. Expertise in the reading of alphabetic scripts, as indexed by the greater left-lateralized N170 activity, is thus related to the ability to simultaneously process a stream of horizontally-arranged letters. This ability may be aided by the ability to detect orthographic regularities via general statistical learning mechanisms. Phonological

mapping is suggested to influence N170 lateralization via a long-term offline process of building orthographic regularity knowledge, possibly through syllabic boundaries and phoneme combination rules, rather than via active phonological processes during the N170 time window.

Ultimately, the findings in this thesis support the position that the N170 component in visual word processing reflects a primarily perceptual stage. At the same time, the critical role of phonological mapping in shaping orthographic regularity, especially in alphabetic scripts, is highlighted. This thesis thus also favors the notion that phonological mapping exerts influence on N170 activity and laterality, albeit via a different mechanism (i.e. offline, long-term process of building orthographic regularity knowledge) than that described in the Phonological Mapping Account (i.e. active phonological processes during the N170 time window).

Relating the findings in this thesis to what is known about reading development and reading disorders, the reduced N1 print tuning effects in dyslexic readers commonly reported in the literature may thus be reflective of their weaker abilities in simultaneous processing of visual stimuli in general. In other words, dyslexic readers may have an impairment in encoding the identities and positions of entities within a string. It would be meaningful for future work to investigate if this impairment is manifested across modalities - both visual and auditory, which would help explain the observed relationship between N1 print tuning and phonological skills in dyslexia research. Further work to determine whether impaired simultaneous processing is a core deficit in dyslexia is also recommended.

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