HOW DOES LEARNING TO READ SHAPE THE NEURAL REPRESENTATION OF SPOKEN AND WRITTEN LANGUAGE?

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DECLARATION OF AUTHORSHIP

I, Adam Jowett, hereby declare that this thesis and the work presented in it is entirely my own. Where I have consulted the work of others, this is always clearly stated.

Signed:

Date: 19/09/2022

To Edith Hilda Jowett

I love you too

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ABSTRACT

Writing systems vary in the way they express the sounds and meanings of spoken language. Alphabetic writing systems contain information about phonological structure within the orthography due to systematic relations between graphemes and phonemes. Logographic writing systems encode less-fine-grained information about phonological structure via more arbitrary mappings between characters and syllables. We tested whether differences in orthographic structure impact on reading acquisition and the spoken language representations that underpin reading (e.g., Rastle et al., 2011). Twenty-four adult participants were trained on two artificial languages with alphabetic and logographic writing systems. Each language contained 24 words denoted by phonological, orthographic, and semantic components. Learning involved completing computerised tasks over 10 days before performance was assessed using behavioural tests. Following training, neural activity was recorded using fMRI whilst participants made meaning judgements about trained spoken and written stimuli.

We assessed the development of mappings between sounds, spellings, and meanings of words and the division of labour between dorsal and ventral reading pathways. Performance was compared using linear mixed-effect models and neural activity was contrasted using paired-samples t-tests. Representational similarity analysis assessed whether alphabetic and logographic systems influence neural sensitivity to phonemic, orthographic, and semantic structure during reading and listening. Overall, alphabetic words exhibited stronger orthography–phonology mappings while orthography–semantic mappings were stronger for logographic words. The dorsal pathway showed greater activity for alphabetic written words; the ventral pathway was more active for logographic written words. Representations only encoded the phonemic/orthographic structure of alphabetic written and spoken words. No orthographic effects on spoken language were observed. These findings advance our understanding of how writing systems impact on reading acquisition and spoken language. They suggest different strategies are used to learn alphabetic and logographic languages and that orthographic transparency can impact on the division of labour and underlying representations.

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In lieu of appendices, experimental materials, data, and analysis scripts are available in the Open Science Framework (OSF) storage for this project: https://osf.io/3q2jb/. Each experimental chapter (i.e., chapters 2-4) has a dedicated folder on the OSF.

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CHAPTER I: GENERAL INTRODUCTION

Maynard-Smith and Szathmáry (1995) famously described human language as the most recent major transition in the evolutionary history of all life on Earth. An exceptional communication system in the natural world, language facilitated the social exchange of thoughts, ideas, and experiences (Fitch, Huber, & Bugnyar, 2010). "Language" describes the suite of cognitive traits enabling humans to acquire and use conventional codes, "languages", to express thoughts as signals and interpret signals as thoughts (Scott-Phillips, 2014; Fitch et al., 2010). Spoken language is an evolved trait, a complex and specialised skill, naturally and universally acquired during childhood through continued immersion and exposure. It develops spontaneously and unconsciously without instruction (Pinker, 1994). By contrast, literacy is a more recent cultural invention, *"an artificial contraption connecting vision and language"* (Pinker, 1994. p. 189). It facilitated the accumulation of knowledge by mapping arbitrary symbols onto languages in a manner that could be recorded (writing) and interpreted (reading). Equipped with literacy, communication could now bridge the gaps of space and time (Pinker, 1994). Pinker (1997) famously wrote: *"Children are wired for sound, but print is an optional accessory that must be painstakingly bolted on"* (p. ix). While spoken language is instinctively acquired, typically during childhood, learning to read and write demands years of dedicated practice and must be taught with formal instruction often with dedicated lessons, all without any guarantee of success (Pinker, 1994). Thus, written language cannot be considered an instinct.

Emphasising the distinction between spoken language and reading is paramount. Before acquiring skills in reading and writing, most of us have developed relative competence in understanding spoken language. Gaining spoken language requires us to learn associations between combinations of sounds (phonology) and the meanings (semantics) they represent. Learning to read means acquiring mappings from print (orthography) onto existing representations of both sounds and meanings (e.g., Plaut, McClelland, Seidenberg, & Patterson, 1996). Figure 1.1 provides an illustration of how a word is represented by an integrated relationship between an associated spelling, sound, and meaning (A) and how meaning can either be accessed directly from the spelling or indirectly via the associated sound (B). It is widely accepted that humans are not born with dedicated neural hardware to support reading. To solve the problem of reading, the brain capitalises on systematicity which may exist within the orthography. However, languages vary in the way that writing expresses the phonological and semantic structure of spoken language. Several "writing systems" are associated with languages, each exhibiting a distinct orthographic structure.

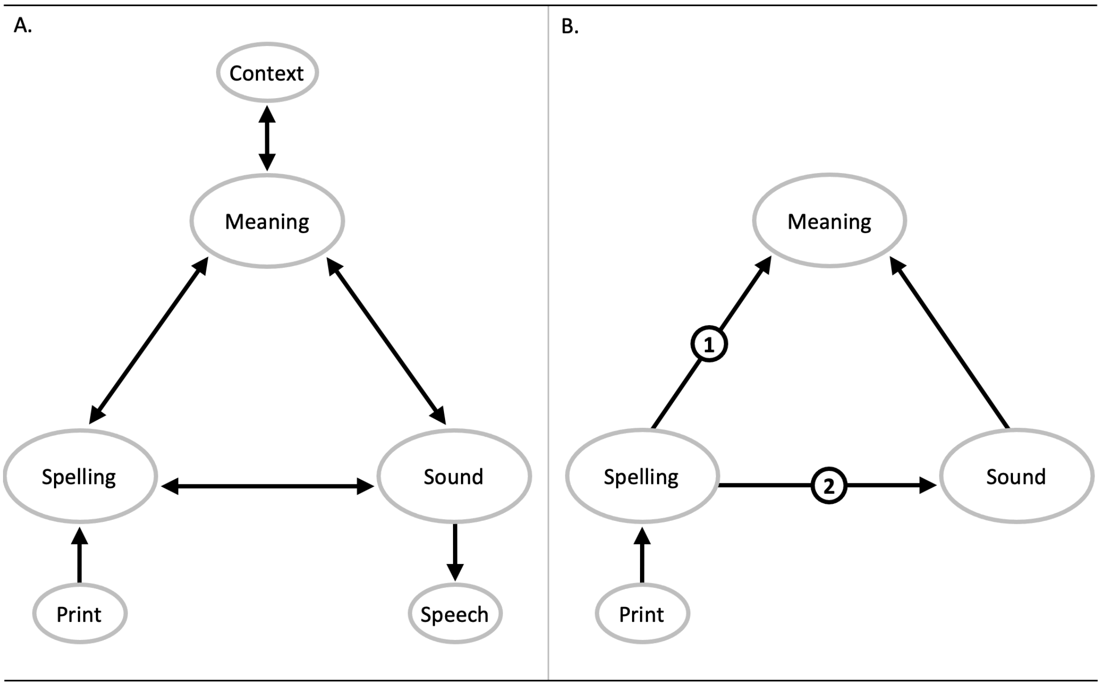


Figure 1.1. An illustration of how words are represented by spellings, sounds, and meanings (A) and how meaning can either be accessed directly from a spelling (B1) or indirectly via an associated sound (B2). The Triangle model comprises cooperative direct and indirect, phonologically mediated reading pathways between orthography, phonology, and semantics (Harm & Seidenberg, 2004). A solution is jointly computed by both pathways depending on the nature of the task (Plaut et al., 1996).

Alphabetic writing systems (e.g., Italian) contain information about phonological structure within the orthography due to regular, one-to-one relations between sounds (phonemes) and symbols (graphemes), known as the “alphabetic principle”. In contrast, logographic writing systems (e.g., Chinese) encode less-fine-grained information about phonological structure via more arbitrary, holistic mappings between characters and syllables. Thus, alphabetic writing systems exhibit greater “orthographic transparency” (Smith, Monaghan, & Huettig, 2021). As the brain capitalises on systematicity which may exist in the orthography, such differences in orthographic structure may impact on the nature of reading acquisition, as well as existing spoken language systems (e.g., Rastle, McCormick, Bayliss, & Davis, 2011).

Central to our investigation is an aim to contribute to ongoing debates surrounding the impact of orthographic transparency on how the brain solves the problem of reading and the nature of orthographic effects on spoken language. Thus, this project will investigate how the orthographic transparency of a writing system impacts on reading acquisition, and on the spoken language representations that underpin reading. We hypothesise that the orthographic transparency of a writing system will determine the division of labour between direct spelling-meaning and indirect spelling-sound-mapping pathways of the reading network during reading aloud and comprehension (see Figure 1.1B). As transparent alphabetic writing systems feature consistent, one-to-one mappings between symbols and sounds, we predict that sub-word spelling-sound information will be favoured, strengthening spelling-sound mappings and increasing reliance on this pathway. Equally, spoken language will be impacted by reading acquisition via “online” orthographic co-activation or “offline” phonological restructuring. Finally, Seidenberg (2011) argued that spelling-meaning is the more efficient mapping. As logographic writing systems lack spelling-sound systematicity (instead featuring arbitrary, whole-word mappings between spelling and sound), we predict that spelling-meaning mappings will consequently be favoured. In addition, we will explore spelling-sound convergence as a common brain signature of literacy by examining variation between languages with different orthographic systems (Rueckl, Paz-Alonso, Molfese, Kuo, Bick, Frost, et al., 2015; Chyl, Kossowski, Wang, Debska, Luniewska, Marchewka, et al., 2019). The study has been designed to address common methodological limitations of previous research by adding to recent studies which teach adults' novel words in laboratory settings (Rastle et al., 2011; Mei, Xue, Lu, He, Zhang, Wei et al., 2014; Taylor, Davis, & Rastle, 2017). Artificial orthography methods and fMRI measures of brain activity were implemented to test how alphabetic and logographic writing systems differentially influence behavioural performance and the nature of emerging neural representations as adults learned to read novel words.

To begin, relevant literature will be reviewed, comparing theoretical perspectives, and detailing previous research to justify the rationale of our investigation and hypotheses. First, computational models underpinning learning to read and associated debates will be compared while considering whether multiple models are required for different writing systems. The nature of existing writing systems and orthographic transparency will then be discussed in greater depth. Next, we will discuss how orthographic transparency impacts on reading acquisition while reviewing evidence for a universal brain signature of successful literacy acquisition across different orthographic systems. Wider impacts of the nature of the writing system on spoken language processing will then be reviewed, including the contribution of "online" orthographic activation and "offline" phonological restructuring. Finally, we will summarise key findings from the literature review and the current state of the topic before defining outstanding research questions and our approach to addressing them. Here, laboratory approaches to studying language learning and the neural basis of reading acquisition will be reviewed. In subsequent chapters, our methodology will be described in greater detail before presenting the findings of the experiment. To close, results will be discussed with reference to the content of the literature review to inform our conclusions.

1.1. Cognitive and Neural Models of Reading

Computational models of reading have revolutionised our understanding of visual word recognition and reading aloud (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). Computer programs perform a task (i.e., comprehending meaning from printed words) using precise information-processing procedures as specified in a theory of how we perform a cognitive activity (Coltheart et al., 2001). The Dual Route Cascaded model (DRC model; Coltheart et al., 2001) and Triangle model (Plaut et al., 1996; Harm & Seidenberg, 2004) aim to capture the cognitive mechanisms underpinning the reading system and have emerged as leading models within the field. Figure 1.2 provides an illustration of the Triangle model (A) and DRC model (B). The Triangle model comprises of cooperative direct and indirect pathways between orthography, phonology, and semantics (Harm & Seidenberg, 2004). A solution is jointly computed by both pathways depending on the nature of the task (Plaut et al., 1996). The DRC model consists of three distinct routes; the lexical semantic, lexical non-semantic, and grapheme-phoneme correspondence route (Coltheart et al., 2001). Much research has adjudicated between these models, but they are broadly similar in many ways.

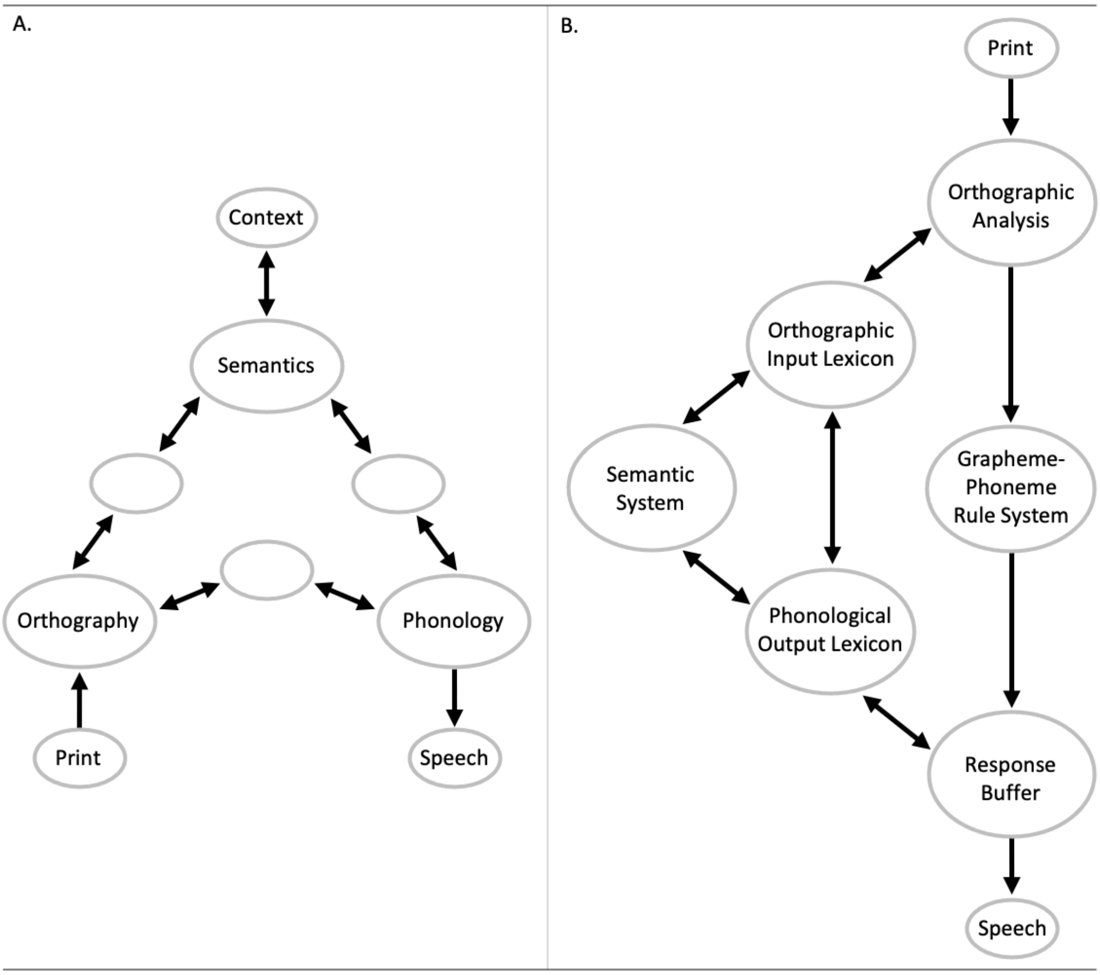


Figure 1.2. An illustration of the Triangle model (A) and DRC model (B) of reading. The Triangle model comprises cooperative direct and indirect pathways between orthography, phonology, and semantics (Harm & Seidenberg, 2004). A solution is jointly computed by both pathways depending on the nature of the task (Plaut et al., 1996). The DRC model consists of three distinct routes; the lexical semantic, lexical non-semantic, and grapheme-phoneme correspondence route (Coltheart et al., 2001).

Comparing Triangle and DRC models

As prominent computational models of reading, the Triangle (Plaut et al., 1996; Harm & Seidenberg, 2004) and DRC (Coltheart et al., 2001) model feature key similarities and differences which must be explored. Both models of reading are based on reading in alphabetic writing systems and successfully capture benchmark findings of English word reading. They similarly aim to capture the cognitive mechanisms that underpin the reading system and describe how sounds and meanings of printed words are computed using whole-word and sub-word information. The Triangle and DRC model both propose that the meaning of printed words can be comprehended using two pathways, or "dual routes"; a direct pathway mapping from print-to-meaning using whole-word information and an indirect pathway mapping from print-to-sound using sub-word information and then sound-to-meaning using existing knowledge of spoken language (Taylor et al., 2017). A distributed connectionist approach, the Triangle model proposes that, during literacy acquisition and skilled reading, a solution is jointly computed by both pathways depending on the nature of the task (Plaut et al., 1996). A symbolic, hard-wired approach, the DRC model focuses on the processes involved in skilled English reading and consists of three mutually exclusive reading routes; lexical semantic, lexical non-semantic, grapheme-phoneme correspondence (Coltheart et al., 2001; see Figure 1.2). Thus, while these models are broadly similar in many ways, fundamental differences exist that may determine whether either can be applied as a universal framework to the wide variety of orthographic systems. Each of these characteristics will be discussed in greater detail in future sub-sections.

Overall, the Triangle and DRC model of reading are both useful frameworks for understanding the complex processes associated with reading. Both computational models embody an assumption that numerous process and different levels of analysis are required (i.e., phonological, orthographic, and semantic processing), and that underlying processes are interconnected, working together to support reading aloud and comprehension. Equally, the Triangle and DRC model have both generated and gain support from a sizable body of empirical research on reading. Nevertheless, notable differences exist that contribute to ongoing debate concerning which model provides the most utility and the most complete and accurate account of the cognitive mechanisms involved in reading. First, the Triangle and DRC model emphasise top-down and bottom-up processing, respectively. The Triangle model highlights the role of context and existing knowledge while the DRC model emphasises visual and phonological characteristics of words. As mentioned previously, while both models of reading incorporate direct and indirect routes, the DRC model defines these routes as lexical (either semantic or non-semantic) and non-lexical (i.e., grapheme-phoneme correspondence). Here, the Triangle model proposes that the indirect, phonologically mediated route is favoured for unknown words, while the DRC model suggests the non-lexical route is used exclusively for such words. In contrast, the Triangle model proposes that the direct route is favoured for known words, while the DRC model suggests the lexical route is responsible for processing familiar words. A defining characteristic of the Triangle model is the proposition that direct and indirect routes interact during processing, converging on a solution depending on the task. However, the DRC model posits that lexical and non-lexical routes operate in parallel.

An important distinction between the Triangle and DRC models of reading is that, while the DRC model focuses on the processes involved in skilled English reading, the Triangle model aims to capture the cognitive processes underpinning skilled reading and literacy acquisition. Thus, the Triangle model is a developmental model of reading while the DRC model can only account for skilled reading. However, previous research suggests that the Triangle model may not be entirely naturalistic with regards to reading acquisition and that, despite assuming much pre-existing knowledge about known words and grapheme-phoneme correspondences, the DRC model could be successful as a developmental model. Powell (2006) investigated whether the Triangle model was a good approximation of naturalistic learning by comparing performance early in training to children in their first year of reading instruction. Initially, non-word reading was weaker and the network made more non-lexical errors than the children. Adaptations were made to the network's training to simulate a more natural learning environment (i.e., training was more incremental, grapheme-to-phoneme correspondences were trained, and the corpus was replaced by words from early childhood reading materials) which considerably improved non-word reading. However, the network continued to make more non-lexical errors than the children, while this may result from the absence of semantic mappings. Combined, Powell's (2006) findings suggest that while the Triangle model can replicate important elements of real-world language learning, it may not be truly naturalistic.

The DRC model of reading is not traditionally considered to be developmental as it does not explain how the reading network develops over time or how children learn to read, and instead focuses on how skilled readers recognise words quickly and easily. Nevertheless, Pritchard et al. (2018) incorporated the self-teaching hypothesis (Firth, 1972) within the DRC model. The self-teaching hypothesis provides an account of how children can create opportunities to increase their reading skill and orthographic knowledge. Here, an interaction between phonological recoding and contextual cues is used to determine the pronunciation of unfamiliar words. Pritchard et al. (2018) investigated how these mechanisms support a child's ability to teach themselves by implementing self-teaching computationally within the DRC model. The ST-DRC simulates recoding using the non-lexical (grapheme-to-phoneme correspondences) route. Unknown printed words activate known spoken words, thereby facilitating an opportunity to increase orthographic knowledge. Equally, mechanisms simulating the role of contextual cues are incorporated into the variant. ST-DRC is consequently able to read irregular words using phonological decoding and contextual information. Pritchard et al's (2018) adaptation of the DRC model demonstrates that, with minor amendments, it may also be successful as a developmental model of reading.

Direct and indirect reading pathways

Based on reading in alphabetic writing systems, the Triangle and DRC model describe how sounds and meanings of printed words are computed using whole-word and sub-word information. Specifically, both models of reading propose that the meaning of printed words can be comprehended using two pathways, or "dual-routes", resolved in the phonological output system; a direct pathway mapping from print-to-meaning using whole-word information and an indirect pathway mapping from print-to-sound using sub-word information and then sound-to-meaning using existing knowledge of spoken language (Taylor et al., 2017). Further, both computational models indicate that item-specific knowledge (i.e., lexical and/or semantic information) and therefore the direct reading pathway are necessary for irregular word reading. Equally, letter-sound knowledge (i.e., rules or statistics for grapheme-to-phoneme mappings) and the indirect, phonologically mediated pathway are important for non-word reading. Decades of neuroimaging and neuropsychological evidence supports the existence of dual reading pathways, with analogues consistently observed within the brain.

Evidence for a ventral reading pathway

Neural evidence consistently points to the direct reading pathway (print-to-meaning) being underpinned by the *ventral* stream, extending from occipital to temporal brain regions in the left hemisphere. Figure 1.3 depicts the location of the ventral stream and direct print-meaning processes on a segmented and inflated brain template. Previous work has identified a graded response to the word-likeness of orthographic stimuli, with representations becoming increasingly abstract from left posterior-to-anterior ventral occipitotemporal cortex (vOT; Vinckier, Dehaene, Jobert, Dubus, Sigman, & Cohen, 2007; Dehaene, Cohen, Sigman, & Vinckier, 2005). Specifically, Vinckier et al. (2007) found increased activity for words and pseudowords compared to stimuli constructed from frequent bigrams, consonants, and false fonts with the same visual complexity as regular letters in left mid-fusiform and inferior temporal gyrus. Moreover, meta-analyses conducted by Taylor, Rastle, & Davis (2013) found left anterior fusiform (FG) and middle temporal gyri (MTG) to be more active for known words than pseudowords, thus supporting the notion that direct print-meaning processes (i.e., identifying meaning using item-specific knowledge and whole-word information) are underpinned by a processing hierarchy along the ventral stream.

Taylor et al. (2013) noted that research into the neural underpinnings of reading is typically directed by cognitive models like the Triangle and DRC model. They compared 36 neuroimaging studies to determine whether model components could predict neural activity during word and pseudoword reading. Taylor et al. (2013) identified clusters of activation for word, pseudoword, irregular and regular word reading and found that the neural basis of the reading system closely converged with the organisation of the reading system proposed by cognitive models. In terms of the

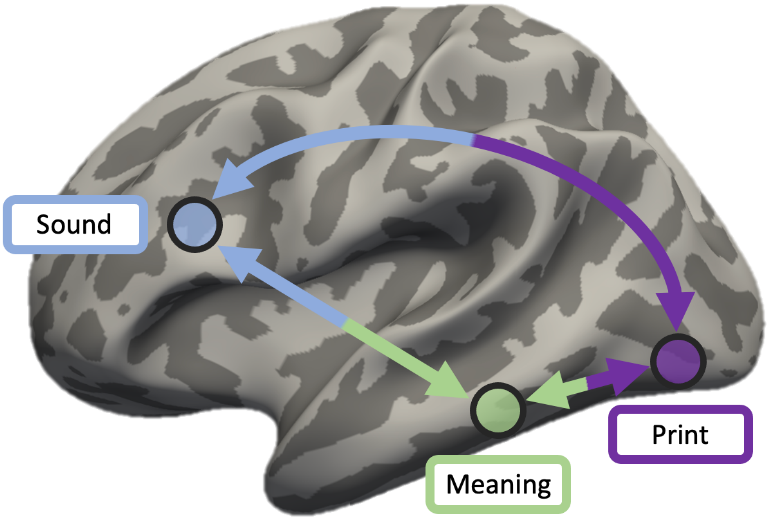


Figure 1.3. The location of ventral (print-to-meaning) and dorsal (print-to-sound-to-meaning) reading pathways on a segmented and inflated template brain anatomy.

ventral reading pathway, left anterior FG and MTG activation clusters consistently reflected lexical and/or semantic processing associated with direct print-meaning processes, while left vOT and inferior frontal gyrus (IFG) were associated with orthographic processing and phonological output computation, respectively. Taylor et al. (2013) concluded that cognitive models of reading can be used to interpret neuroimaging studies which can consequently serve to advance cognitive models. Finally, correspondence between the direct pathway and ventral stream is supported by connectivity analyses and neuropsychological evidence (Bouhali, de Shotten, Pinel, Poupon, Mangin, Dehaene, et al., 2014; Purcell, Shea, & Rapp, 2014; Tsapkini & Rapp, 2010). For example, left anterior FG displays connectivity with anterior temporal regions associated with semantic processing (Bouhali et al., 2014) and has been associated with impaired reading and spelling for words compared to pseudowords when damaged (Purcell et al., 2014; Tsapkini & Rapp, 2010).

Evidence for a dorsal reading pathway

The *dorsal* stream appears to underpin indirect, phonologically mediated reading (print-to-sound-to-meaning) and includes the left posterior vOT, inferior parietal sulcus, and superior regions of the inferior frontal gyrus (opercularis and triangularis; Taylor et al., 2013). Figure 1.3 depicts the location of the dorsal stream and phonologically mediated reading processes on a segmented and inflated brain template. Meta-analyses conducted by Taylor et al. (2013) revealed that these brain regions consistently display increased activity for alphabetic pseudowords than known English words, more specifically that left inferior parietal cortex activity reflects spelling-sound conversion. As systematic mappings between letters and sounds are capitalised upon to decode alphabetic pseudowords, these regions appear to support the phonologically mediated reading pathway (i.e., identifying meaning using sub-word information). Further, Taylor et al., (2017) similarly found evidence supporting the existence of a dorsal reading pathway underpinning print-to-sound processes by comparing different methods of reading instruction using artificial orthographies.

Print-to-sound mappings should be emphasised when learning to read alphabetic languages, but considerable variation still exists across English-speaking countries. Taylor et al. (2017) compared different methods of reading instruction by teaching native English-speaking adults to read two sets of novel words written in artificial orthographies. Participants were pre-trained on sounds and meanings before novel written words were introduced and trained over the subsequent eight days. Print-to-sound mappings were emphasised when training one set of novel words; print-to-meaning mappings were emphasised for the other set. Behavioural results showed that print-to-sound training benefitted reading aloud, generalisation, and comprehension.

In terms of the dorsal reading pathway, univariate fMRI analyses revealed that print-to-meaning focused training caused increased neural effort in associated brain areas involved in reading aloud. These results further implicate dorsal pathway regions as being involved in spelling-sound conversion using sub-word information and letter-sound knowledge (i.e., grapheme-to-phoneme mappings). Crucially, multivariate fMRI analyses validated their artificial orthography methods, revealing a highly similar distribution of neural activity when reading artificial and English words.

Moreover, Bolger, Perfetti and Schneider (2005) found greater neural activation for alphabetic than logographic writing systems in left inferior parietal cortex. As systematic grapheme-to-phoneme mappings characterise both alphabetic writing systems and the decoding of pseudowords, Bolger et al's (2005) findings lend further support to the dorsal stream underpinning the phonologically mediated reading pathway. Bouhali et al. (2014) found left posterior occipitotemporal cortex to be connected to frontal and temporal regions associated with speech processing (i.e., left inferior frontal, posterior middle, superior temporal gyri). Finally, slower, more effortful reading of alphabetic words has been associated with damage to left posterior occipitotemporal cortex (Roberts et al., 2013), while patients with damage to left inferior parietal cortex and left IFG demonstrated impaired pseudoword reading compared to known words (Rapcsak et al., 2009; Woollams & Patterson, 2012). Notably, phonological information from both ventral and dorsal reading pathways appears to be resolved by the left inferior frontal gyrus (Taylor et al. (2013).

Accounting for different writing systems

The Triangle model and DRC model similarly aim to capture cognitive mechanisms underpinning the reading system (Harm & Seidenberg, 2004; Coltheart et al., 2001). While both models successfully capture benchmark findings of English word reading, considerable variation between different orthographic systems must be considered to comprehensively understand the cognitive mechanisms that underpin reading (Smith et al., 2021). As described, writing systems vary substantially in the extent to which information about the phonological structure of spoken language is encoded by the orthography. Thus, an important question emerges concerning whether multiple computational models are required to account for different writing systems and orthographic structures (Smith et al., 2021). Despite many similarities existing between the Triangle and DRC model, we must continue exploring their differences to assess whether either can account for reading in different orthographic systems.

A symbolic, hard-wired approach, the DRC model focuses on describing the processes involved in skilled English reading (see Figure 1.2B; Coltheart et al., 2001). Here, mutually exclusive pathways from spelling to meaning are emphasised (e.g., visual versus phonological; Seidenberg, 2011). The DRC model theorises that the direct pathway from print-to-meaning uses whole-word, item-specific knowledge (i.e., lexical and/or semantic information) to comprehend the meaning of irregular words. Alternatively, the phonologically mediated pathway from print-to-sound-to-meaning is used to decode regular words using sub-word information and existing knowledge of spoken language. In contrast, the Triangle model aims to capture the cognitive mechanisms underpinning learning to read and skilled reading (Figure 1.2B; Plaut et al., 1996; Harm & Seidenberg, 2004). A distributed, connectionist approach, the

Triangle model represents one underlying architecture that develops via general statistical learning mechanisms. The critical concept is the “division-of-labour”, a theory proposed by (Plaut et al., 1996) and exemplified by the Triangle model. Unlike the either/or approach emphasised by the DRC model, the meaning of a printed word is jointly computed by direct (print-to-meaning) and phonologically mediated (print-to-sound-to-meaning) pathways (see Figure 1.3). The reading network identifies a solution depending on the nature of the task, converging on the most efficient division of labor between direct and phonologically mediated pathways depending on their necessity for producing the desired response (Seidenberg, 2011; Taylor et al., 2017). Such differences have important implications for whether the Triangle model and DRC model of reading can be applied to the wide variety of orthographic systems.

Plaut et al. (1996) established a view that the reading system consists of a cooperative division of labor between direct and phonologically mediated pathways to meaning that must work together to facilitate word and non-word reading. As computational realisations of the dual-route theory of reading, the Triangle and DRC models both describe how sounds and meanings of printed words are computed using whole-word and sub-word information. However, the Triangle model uniquely accounts for the processes involved in reading acquisition while embodying the division of labor approach. Plaut et al. (1996) proposed that the reading system gradually gains sensitivity to the statistical structure of orthographic, phonological, and semantic representations. Thus, the network converges on a solution depending not only on the nature of the task (i.e., computing meaning from print) and pressure for accuracy and efficiency, but the properties of the writing system and language it represents (Plaut et al., 1996; Seidenberg, 2011). In a system mapping between different codes, the nature of the mappings impacts on the division of labor between direct and phonologically mediated pathways from print to meaning (Harm & Seidenberg, 2004).

Overall summary

In conclusion, the one architecture-multiple solutions theory established by the Triangle model presents the most useful framework to formulate hypotheses about how the nature of a writing system impacts on reading acquisition and the spoken language representations that underpin reading (Seidenberg, 2011). Smith et al. (2021) trained a connectionist neural network model based on the Triangle model on artificial corpora representing the full range of extant writing systems. As they replicated key behavioural and neuroscientific results, Smith et al. (2021) similarly concluded that the Triangle model is an effective model of reading acquisition and skilled reading that can be universally applied to the wide variety of orthographic systems. In contrast, Coltheart et al., (2001) argue against universals of written language; *"The Chinese, Japanese, and Korean writing systems are structurally so different from the English writing system that a model like the DRC model would simply not be applicable"* (p. 236). Thus, the DRC model may only account for skilled English reading and cannot be used to form hypotheses about the variety of different orthographic systems.

1.2. Writing Systems and Orthographic Depth

Learning to read requires acquiring mappings from orthography onto existing phonological and semantic representations (Plaut et al., 1996). To solve the problem of reading, the brain capitalises on systematicity that may exist within the writing system (e.g., phonological or morphological). However, orthographic systems vary in the extent they encode a language's phonological and semantic structure (i.e., how they express the sounds and meanings of spoken language; Smith et al., 2021). Comrie (2013) defines five categories of orthographic system used to describe those found globally: alphabetic, consonantal, alphasyllabic, syllabic, and logographic. Each category exhibits a distinct orthographic structure that varies in the extent to which the written form of a word encodes the phonology, known as orthographic transparency (Smith et al., 2021). In the following paragraphs, the five categories of orthographic system will be described in order from most to least orthographically transparent.

Alphabetic writing systems contain information about phonological structure within the orthography due to regular systematic relations between sounds and symbols. The basic unit of linguistic structure represented most directly by alphabetic systems are the individual letters or groups of letters (graphemes) which map onto individual sounds (phonemes; Smith et al., 2021). Psycholinguistic Grain Size theory (Ziegler & Goswami, 2005) distinguishes between large linguistic units or "grains" like words and phrases and smaller, fine-grained elements like morphemes and individual letters and sounds. As systematic, one-to-one mappings exist between individual graphemes and phonemes, alphabetic orthographies encode *"detailed information regarding the fine-grained phonological structure of the language"* (Smith et al., 2021, p.126). Shallow alphabetic writing systems (i.e., Italian) feature a near perfect one-to-one mapping between individual graphemes and phonemes, while deep alphabetic systems (i.e., English) deviate from the strict regularity and consistent granularity of mappings between orthography and phonology. For example, a single letter may correspond to multiple phonemes (e.g., flint and pint) or a single phoneme may be associated with different combinations of letters (e.g., cot and yacht; Smith et al., 2021).

Consonantal writing systems (i.e., Hebrew and Arabic) closely resemble the structural properties of alphabetic writing systems with one defining characteristic; only consonants, not vowels are represented after children reach 12 years old (Comrie, 2013). When a child learns to read and write in Hebrew or Arabic, vowels are written into the orthography, and the writing system is therefore highly consistent. Once the child reaches 12 years old, vowels are removed from their texts and only consonants continue to be represented by the writing system. Graphemes within alphasyllabic writing systems (i.e., Thai) similarly represent only consonants, while diacritics or other transformations indicate the presence of a specific vowel preceding or following the grapheme (Smith et al., 2021). In a syllabic writing system (i.e., Japanese Kana; Hiragana and Katakana), the basic unit of representation is the syllable. Each syllable within the phonology corresponds with a single character within the orthography (Smith et al., 2021). Finally, logographic writing systems (i.e., Chinese and Japanese Kanji) encode less-fine-grained information about phonological structure via more arbitrary mappings between characters and syllables. Here, the basic representational unit is the morpheme; characters relate to meaning rather than the phonological properties (phonemes) represented by the other writing systems described.

Chinese words typically feature a combination of two characters (symbols representing a word or concept) which contain information about the word’s pronunciation and meaning: phonetic and semantic radicals, respectively (Shu, Chen, Anderson, Wu, & Xuan, 2003; Katz & Frost, 1992). While phonetic and semantic radicals contain some information about the character/word's sound and meaning, neither communicate exactly how a character/word should be pronounced or what it means, plus the information provided is not often entirely reliable and offers limited capacity for generalisation. However, their combination is highly constraining and supports the reader to identify a character/word's meaning using the written form (Seidenberg, 2011). Further, some Chinese words contain more than two characters, some are comprised of pictograms or pictographs (characters that resemble the objects, concepts, and ideas they represent), while others are ideograms (characters representing concepts or ideas which provide no indication of the word's phonetic or semantic properties; Huang & Hanley, 1995). For example, 木 (tree), 林 (forest), and 森 (wood) are all pictographs. The character for "tree" looks like a tree, the "forest" character contains two tree-pictographs, while the "wood" character contains three tree-pictographs. In summary, substantial variation exists in how extant writing systems encode phonological information. Considerable evidence suggests that such differences in orthographic structure impacts on the nature of reading acquisition (Seidenberg, 2011). In the following section, we will continue by evaluating research investigating how orthographic transparency impacts on learning to read.

1.3. Orthographic Depth and Reading Acquisition

As outlined in the previous section, languages vary in the way that writing expresses the phonological and semantic structure of spoken language. Transparent alphabetic writing systems (e.g., Italian) contain information about phonological structure within the orthography due to systematic, one-to-one mappings between graphemes and phonemes. In contrast, opaque logographic writing systems (e.g., Chinese) encode less-fine-grained information about phonological structure via more arbitrary, holistic mappings between spellings and sounds. Such variation in orthographic structure may have notable implications for the nature of reading acquisition and skilled reading. Psycholinguistic Grain Size theory (Ziegler & Goswami, 2005) proposes that people who read opaque orthographies decode the meaning of words using large orthographic elements (i.e., whole word lexical-semantic information), mediating the impact of inconsistent spelling-sound relations. However, shallow orthographic systems enable people to rely on smaller orthographic elements (i.e., consistent grapheme-phoneme mappings) while reading accurately and efficiently (Goswami, Ziegler, Dalton, & Schneider, 2003). Thus, different writing systems may require different aspects of the reading system depending on the relationship between spelling and sound.

The Triangle model proposes that the reading network will converge on the most efficient division of labor between direct (print-to-meaning) and phonologically mediated (print-to-sound-to-meaning) pathways depending on the statistical structure of the writing system and language it represents (Harm & Seidenberg, 2004; Plaut et al., 1996; Seidenberg, 2011; Taylor et al., 2017). While the sounds and meanings of written words can be jointly determined by both pathways, the nature of the writing system may impact on the development of direct and indirect pathways during the course of learning, and consequently on reading aloud and comprehension (Taylor et al., 2017). Due to differences in the relationship between orthography and phonology, readers may favour sub-word spelling-sound information for transparent alphabetic words and whole word lexical-semantic information for opaque logographic words. For instance, the indirect, phonologically mediated pathway (O-P-S) may largely be able to facilitate reading aloud and comprehension in orthographies with high transparency between spelling and sound. The direct pathway (O-S) may only be required when inconsistencies exist between spelling-sound mappings (Share, 2008; Taylor et al., 2017; Ziegler & Goswami, 2005). In contrast, the O-S and ventral pathway may be favoured by logographic writing systems lacking O-P systematicity (instead featuring arbitrary, whole-word mappings between spelling and sounds) as benefits otherwise offered by the phonologically mediated pathway are outweighed by the greater effort required to acquire O-P mappings (Seidenberg, 2011).

Existing research supports the assertion that the degree of transparency between spelling and sound may have important consequences for reading acquisition and skilled reading; *"such variation is likely to have major implications for how the reading system operates"* (Smith et al., 2021; p. 125). Smith et al. (2021) investigated how the full range of orthographic systems (alphabetic, alphasyllabic, consonantal, syllabic, logographic; see section 1.2) impact on both the developing and skilled reading system by training a connectionist neural network model on artificial corpora. Based on Harm and Seidenberg's (2004) implementation of the Triangle model of reading, Smith et al's (2021) models simulated the reading process by implementing the many ways orthographic systems express the sounds and meanings of spoken language. Phonological and semantic representations and mappings were identical for each writing system and model training and testing parameters were controlled. This approach aimed to isolate the contributory effect of orthographic structure while training the models on artificial corpora to neutralise covarying linguistic and sociocultural variables previous studies have been susceptible to. Thus, Smith et al. (2021) conducted a highly controlled comparison of models simulating multiple writing systems to investigate how different orthographies impact on the division of labour between direct and indirect reading routes. Equally, the study explored whether the consequent nature of the reading system can explain behavioural differences in reading performance and whether the Triangle model of reading is effective as a universal framework that can be applied to the full range of orthographic systems.

Smith et al. (2021) observed processing differences within the network that emerged due to the nature of different writing systems and the relationship between spelling and sound. Orthographic transparency influenced both how the model solved reading comprehension and reading aloud and the continued operation of the reading system following training. Specifically, the ratio between O-P-S to O-S was much greater for orthographically transparent (i.e., alphabetic) compared to opaque (i.e., logographic) writing systems during reading comprehension. Moreover, the ratio between O-P to O-S-P was also much greater for transparent than opaque writing systems during reading aloud. Thus, Smith et al's (2021) results suggests that transparent writing systems favoured O-P mappings while opaque logographic systems favoured O-S during reading comprehension and reading aloud, and that the division of labour between direct and indirect reading routes is determined by nature of the writing system. Smith et al. (2021) concluded that the Triangle model of reading is effective as a universal framework that can be applied to the full range of orthographic systems and that processing of the reading system can be constrained by specific properties of the writing system. Their simulations both replicated and offered explanation of behavioural differences in reading performance and previous neuroimaging results. For example, Mei et al. (2014) explored phonological access via linguistic units with different grain sizes using neuroimaging and artificial orthography methods.

Mei et al. (2014) aimed to identify brain regions underpinning phonological access via large linguistic units (whole words) and smaller, fine-grained units (graphemes and phonemes). Two groups of native English-speaking participants learned to read aloud an artificial language inspired by Korean Hangul via either consistent, one-to-one grapheme-to-phoneme mappings (assembled) or whole word mappings (addressed) over an eight-day period. fMRI analyses revealed distinct neural pathways for phonological access via grapheme-to-phoneme and whole word mappings. Left precentral gyrus/inferior frontal gyrus and supramarginal gyrus along the dorsal reading pathway were more active when participants read aloud the assembled phonology; anterior cingulate cortex, posterior cingulate cortex, right orbital frontal cortex, angular gyrus and middle temporal gyrus along the ventral pathway showed greater activity for the addressed phonology. These results support dual-route models of reading and the assertion that orthographic transparency may impact on reading acquisition as distinct neural pathways were identified for phonological access from assembled (transparent) and addressed (opaque) orthographies. As transparent alphabetic writing systems feature similar grapheme-to-phoneme mappings and opaque logographic systems exhibit whole word mappings, these results indicate that different neural pathways, perhaps underpinning indirect (O-P-S) and direct (O-S) routes, may be favoured during reading acquisition. Further, investigations of pseudoword and known word reading may also benefit our understanding of the potential impact of orthographic transparency on the developing reading system.

Alphabetic writing systems likely facilitate the same fine-grained analysis of grapheme to phoneme mappings that characterises pseudoword reading, while opaque logographic systems may encourage whole-word analysis associated with known word reading. Taylor et al. (2019) and Vinckier et al. (2007) described a processing hierarchy along left posterior to anterior occipitotemporal cortex (vOT); neural activation was greater for pseudowords than words in posterior vOT and words than pseudowords in anterior vOT. Moreover, previous research suggests that regions associated with spelling-sound conversion and phonological processing for visual stimuli are more active for written pseudowords than known words (Fiebach, Friederici, Müller, & Von Cramon, 2002; Taylor, Rastle, & Davis, 2014; Taylor et al., 2013; Fischer-Baum, Kook, Lee, Ramos-Nuñez, & Vannucci, 2018; Jobard, Vigneau, Simon, & Tzourio-Mazoyer, 2011; Mechelli, Josephs, Lambon Ralph, McClelland, & Price, 2007) and regions associated with semantic processing are more active for words than pseudowords (Binder, Desai, Graves, & Conant, 2009). As alphabetic writing systems and pseudoword reading may facilitate the same analysis of grapheme to phoneme mappings and logographic writing systems and known word reading may encourage whole-word analysis, these finding similarly suggest that alphabetic systems will favour the dorsal reading pathway while logographic systems will favour the ventral pathway (see Figure 1.3 for the location of dorsal and ventral reading pathways on a segmented and inflated brain template). Equally, we would predict the existence of a shift from greater neural activation for alphabetic than logographic pseudowords to the opposite along the left posterior to anterior vOT. Nevertheless, while the orthographic transparency of a writing system may impact on the division of labour between dorsal and ventral pathways, convergent neural activity for speech and print has been identified in many brain regions, with limited variation between languages with different writing systems (Rueckl et al., 2015; Chyl et al., 2019).

Differences in the relationship between spelling and sound may have important consequences for how the brain solves the problem of reading. However, certain characteristics of spoken and written language processing are perhaps invariant to differences in the orthographic transparency between spelling and sound. Thus, to comprehensively assess the impact of the nature of the writing system, we must also account for consistency between writing systems despite differences in the relationship between orthography and phonology. The lack of time for the evolution of specialised areas for processing written language would suggest that spoken language areas might also be recruited for reading (Dehaene & Cohen, 2007). There are few imaging studies that investigate word and pseudoword recognition across both visual and auditory modalities. Ludersdorfer, Schurz, Richlan, Kronbichler, and Wimmer (2013) explored neural activity evoked by such tasks in left-lateralised vOT. Their results led to the conclusion that activation in this brain region is likely associated with the engagement of orthographic representations in both modalities, which appear to aid decoding in difficult auditory tasks. Further, Rueckl et al. (2015) posit that the convergence of spoken and written language processing onto a shared network of neural regions and structures is *"a universal hallmark of successful literacy acquisition"* (p. 15510).

Previous research has revealed convergent neural activity for speech and print in many cortical brain regions associated with phonological and semantic processing (Rueckl et al., 2015; Chyl et al., 2019). Crucially, limited variation has been observed between languages with different writing systems. Rueckl et al. (2015) investigated proficient adult readers of Spanish, English, Hebrew, and Chinese, languages with writing systems representing spoken words orthographically in highly contrasting ways. Participants performed a semantic categorisation task focusing on spoken and written forms while neural responses were recorded using fMRI. They observed extensive speech-print convergence in frontotemporal and parietal regions including bilateral inferior frontal gyrus (IFG), middle temporal (MTG) to superior temporal gyri (STG), and left inferior parietal lobule, with limited variation between languages across multiple analyses. Rueckl et al. (2015) concluded that speech-print convergence emerges *"as a common brain signature of reading proficiency across the wide spectrum of selected languages, whether their writing system is alphabetic or logographic, whether it is opaque or transparent, and regardless of the phonological and morphological structure it represents"* (p. 15510). However, convergence was greater for transparent than opaque writing systems in regions associated with phonological processing (left supramarginal gyrus and supplementary motor cortex) and greater for opaque than transparent writing systems in regions associated with semantic processing (left angular gyrus, fusiform gyrus (FG), middle temporal gyrus (MTG), inferior temporal gyrus). Nevertheless, these variations were relatively minor and all languages demonstrated convergence in the previously stated brain regions.

Moreover, Chyl et al. (2019) compared the development of spoken and written language processing systems in transparent (Polish) and comparably opaque (English) languages. Similarly limited variation was observed between languages when seven-year-old children attended to known written and spoken words during an fMRI scan. Speech-print convergence was most evident in left fronto-temporal regions including IFG while Region of Interest (ROI) analyses revealed it to be greater for Polish than English in regions associated with phonological processing (right STG and MTG) and greater for English than Polish in regions associated with lexical processing (left FG). Chyl et al. (2019) concluded that speech-print convergence is a universal signature of reading even during early stages of acquisition, while similarly small variations result from differences in the relationship between orthography and phonology. If the nature of speech-print convergence was found to be invariant to differences in orthographic transparency, this could be considered an argument against the division-of-labour between reading pathways being dependent on orthographic depth. In the following section, we will continue exploring the potential impact of orthographic transparency by considering orthographic effects on existing spoken language systems.

1.4. Orthographic Effects on Spoken Language Processing

Spoken language is an evolved trait, spontaneously and universally acquired through continued exposure, typically during childhood. It is widely accepted that humans are born with dedicated neural hardware to support spoken language acquisition and processing (speech perception and production). A more recent cultural invention, learning to read and write demands many years of formal instruction without support from comparably dedicated structures within the brain. Literacy acquisition means acquiring mappings from print (orthography) onto existing sounds (phonology) and meanings (semantics; e.g., Plaut et al., 1996). Thus, *“there is a broad consensus that individuals’ experience with the sounds of words (phonology) plays a powerful role in their learning to read and in adult visual word processing”* (Rastle et al., 2011; p. 1588). Language sub-systems that support reading acquisition and written language processing are characterised as being dependent on phonological awareness, the ability to recognise and manipulate units of sound (Pinker, 1997; Ziegler, Bertrand, Tóth, Csépe, Reis, Faísca, et al., 2010). Equally, theoretical and empirical evidence suggests that other factors like orthographic transparency may impact on reading acquisition (see section 1.3). However, less is known about how literacy acquisition impacts on phonological processing (phonemic awareness) and spoken language systems.

Early work demonstrated that acquiring literacy improves phonemic awareness. For example, Morais et al. (1979) investigated whether illiterate and literate adults could add or delete a phoneme to the beginning of a pseudoword. They found that illiterate adults were unable to perform the task while matched participants who learned to read during early adulthood could easily manipulate phonemes. Thus, Morais et al. (1979) concluded that phonemic awareness does not develop spontaneously during childhood and instead requires an individual to learn to read an alphabetic writing system. In addition, historical research has demonstrated we are faster to judge the similarity of two spoken words when they are spelled similarly compared to when they are spelled differently (e.g., *toast-roast* versus *toast-ghost*; Seidenberg & Tanenhaus, 1979). Such findings appear to indicate that orthographic information is co-activated during the task, while it is unclear whether orthographic activation occurs during spoken word processing or the decision-making element of such tasks (Rastle et al., 2011).

More convincing was a training study conducted by Rastle et al. (2011). They trained participants on spoken forms of words and their associated pictures on Day One, then introduced spelling-sound consistent or inconsistent spellings on Day Two, before assessing the influence of these spellings on speech processing tasks on Day Three. Rastle et al. (2011) observed orthographic involvement in speech perception and production tasks that do not require orthographic processing or involve meta-linguistic judgments (i.e., auditory lexical decision and picture naming) having manipulated spelling-sound consistency with perfect experimental control. Thus, Rastle et al.

(2011) concluded that orthographic information impacts on phonological processing and spoken language representations when spelling-sound consistency is manipulated as part of *"a highly interactive language system in which there is a rapid and automatic flow of activation in both directions between orthographic and phonological representations"* (p. 1588). Moreover, Damian & Bowers (2003b) similarly tested skilled readers and concluded that orthographic information may be activated during speech production. However, while previous work may evidence an orthographic effect on phonological processing and spoken language representations, findings are somewhat inconsistent. For example, Damian & Bowers (2009) found no evidence of orthographic effects on speech perception and production. As orthographic systems vary substantially in the extent they encode a language's phonological and semantic structure, potential orthographic effects on phonological processing and spoken language representations may be modulated by different writing systems.

As discussed in previous sections, languages vary in the way that writing expresses the phonological and semantic structure of spoken language. As the brain capitalises on systematicity which may exist in the orthography, such differences in orthographic structure may impact on existing spoken language systems. Given the substantial variation in how the phonological and semantic structure of spoken language can be represented orthographically, learning to read may impact on phonological processing in different ways depending on the nature of the orthographic system (Brennan, Cao, Pedroarena-Leal, McNorgan, & Booth, 2012). For example, alphabetic writing systems may impact on phonological processing due to systematic, one-to-one mappings between graphemes and phonemes. The relationship between fine-grained linguistic units (individual letters and sounds; Ziegler & Goswami, 2005) means *"detailed information regarding the fine-grained phonological structure of the language"* (Smith et al., 2021, p.126) is encoded by the orthography. Consequently, learning to read alphabetic orthographies may facilitate finer-grained phonological processing than writing systems that only encode larger linguistic units.

Logographic systems feature more arbitrary, whole-word mappings between spellings and sounds. Thus, the orthography contains little information about phonological structure (Smith et al., 2021). As logographic orthographies encode less fine-grained information about phonological structure and cannot facilitate similarly granular processing, existing spoken language systems are expected to be largely unaltered by literacy acquisition. Thus, only alphabetic orthographies would be expected to impact on phonological processing (i.e., phonemic awareness; see Morais et al., 1979). Nevertheless, as the Triangle model of reading (Plaut et al., 1996; Harm & Seidenberg, 2004) proposes that a solution to a task is jointly computed by direct (semantic) and indirect (phonological) pathways depending on the nature of the task (see section 1.1), learning to read logographic writing systems may impact on phonological processing to some extent but to a lesser degree than alphabetic orthographies. Brennan et al. (2012) concluded that the phonological awareness network and neural processing of phonology is only enhanced by learning to read transparent alphabetic writing systems, not opaque logographic systems. They only found developmental benefits for English speakers in brain regions associated with the phonological network (i.e., left superior temporal gyrus, inferior parietal lobule, and inferior frontal gyrus).

Should an orthographic effect on phonological processing exist for orthographically transparent writing systems, there is ongoing debate surrounding whether this phenomenon is caused by "online" orthographic co-activation (where orthographic information is activated alongside spoken language representations) or "offline" phonological restructuring (where phonological representations are shaped by the acquisition of literacy). The online co-activation account posits that phonological processing is influenced by connections to and from related orthographic information which is activated during speech processing tasks that do not explicitly require orthographic processing (i.e., auditory lexical decision; see Rastle et al., 2011). In contrast, the phonological restructuring hypothesis indicates that phonological processing is fundamentally shaped by the ability to map between phonological and orthographic representations acquired when learning to read, and that this is reflected in lesser overlap in phonological representations for words like *toast* and *ghost* compared to *toast* and *roast* (Muneaux & Ziegler, 2004). Here, orthographic effects on phonological processing are similarly exerted following literacy acquisition, but orthographic information is not activated during speech processing. Finally, literacy acquisition may cause some combination of both online orthographic co-activation and offline phonological restructuring, and perhaps the relationship between these two processes depends on the nature of the orthographic system (Smith et al., 2021).

Smith et al. (2021) investigated how learning to read impacts on phonological processing by training a connectionist neural network model on artificial corpora representing the full range of extant orthographic systems (alphabetic, alphasyllabic, consonantal, syllabic, logographic; see section 1.2). Section 1.3 provides additional information about Smith et al's (2021) highly controlled comparison of models which aimed to simulate the reading process by implementing the many ways writing systems express the sounds and meanings of spoken language (see page 42). Smith et al. (2021)

observed processing differences within the network that emerged following literacy acquisition (i.e., after computational models were trained on orthographic mappings). Here, orthographic effects on phonological processing were modulated by the nature of the writing system on which the reading system was trained (i.e., the relationship between spelling and sound). Crucially, the structure of phonological representations was impacted by literacy acquisition in some orthographic systems in both the presence (online orthographic co-activation) and absence of orthographic information (phonological restructuring). However, a graded effect of orthographic transparency was only found during reading comprehension tasks which required orthographic activation. No orthographic effect was found during semantic comprehension tasks that do not cause orthographic activation, thus questioning previous findings (i.e., Rastle et al., 2011; Pattamadilok et al., 2010). Smith et al. (2021) concluded that orthographic effects on phonological processing can result from both phonological restructuring and online orthographic coactivation, with distinct and greater effects on phonological processing observed in the presence of orthographic information.

1.5. Conclusions and Issues for Further Research

An experimental paradigm that successfully addresses methodological limitations of previous research and gaps within the current body of literature would constitute a valuable contribution to the field. Such an investigation is required to support ongoing debates concerning how the nature of the writing system may impact on learning to read and the spoken language representation that underpin reading (i.e., "online" orthographic co-activation versus "offline" phonological restructuring), a central aim of this research project. Inspired by Taylor et al. (2017) and Smith et al. (2021), we have designed a new experimental procedure to address our research questions and hypotheses. In addition, the present study will enable the comparison of human and model simulations and whether these approaches can work together to reveal how various factors (e.g., input, training, prior knowledge) shape learning. Furthermore, use of Representational Similarity Analysis (RSA) will advance the existing body of literature beyond comparisons of neural activation. RSA builds on univariate analyses of activation and focuses on the nature of the underlying neural representations by decoding the informational content of different regions. Here, we will investigate whether the orthographic transparency of a writing system impacts on neural sensitivity to orthographic, phonological, or semantic structure by exploring the nature of neural representations underpinning spoken and written language processing (Kriegeskorte, Mur, & Bandettini, 2008). Finally, we will explore the existence and location of convergent neural activity for spellings and sounds considering previous research identifying speech-print convergence as a common signature of literacy, invariant of the orthographic system (Chyl et al., 2019; Rueckl et al., 2015).

Given the findings of the previous research reviewed within this chapter, we hypothesise that the orthographic transparency of a writing system will determine the division of labour between dorsal (orthography to phonology; O-P) and ventral (orthography to semantics; O-S) pathways of the reading network during reading aloud and comprehension. As transparent alphabetic writing systems feature consistent, one-to-one mappings between symbols and sounds, sub-word spelling-sound information will be favoured, strengthening O-P mappings, and increasing reliance on the dorsal pathway. Equally, while previous findings are inconsistent, we predict that spoken language processing will be uniquely impacted by alphabetic writing systems with high transparency between spelling and sounds via either phonological restructuring or online orthographic co-activation. In addition, Seidenberg (2011) argued that O-S is the more efficient pathway due to whole-word mappings requiring less granular processing. As logographic writing systems lack O-P systematicity (instead featuring arbitrary, whole-word mappings between spelling and sounds), O-S and the ventral pathway will be favoured. Finally, as previous research has identified speech-print convergence as a common signature of literacy with limited variation between writing systems (Chyl et al., 2019; Rueckl et al., 2015), we expect to observe neural activation within similar brain regions for known alphabetic and logographic words. Next, current laboratory approaches to studying literacy acquisition will be discussed before introducing the consequent approach taken by the present study in greater detail.

1.6. Laboratory Approaches to Studying Literacy Acquisition

The present study has been designed to address common methodological limitations of previous research by adding to recent studies teaching adults' novel words in laboratory settings (see Rastle et al., 2011; Mei et al., 2014; Taylor et al., 2017, 2019). Previous research has traditionally preferred between-subjects designs, comparing different groups of participants and their knowledge of existing monoscriptal writing systems (Brennan et al., 2012). Here, training is simple or unnecessary, plus the complex nature of existing writing systems enables the selection of stimuli with highly specific characteristics. However, such an approach fails to control for prior knowledge, specific stimulus properties (e.g., idiosyncratic qualities), and semantic associations between stimuli. Experimental manipulations are also limited by the complexity of existing writing systems. For example, it is not possible to deconfound phonological and orthographic information within alphabetic writing systems, due to the systematic one-to-one mappings between sound and spelling. Studies which capitalise on biscriptal orthographies benefits from similarly limited training, while a cleaner experimental manipulation is possible. Nevertheless, this approach is equally susceptible to uncontrolled prior knowledge, idiosyncratic properties, and semantic associations. Finally, previous empirical research utilising bilingual participants and a within-subjects design is similarly problematic as prior knowledge and the potential impact of bilingualism on processing different writing systems cannot be controlled.

In contrast, artificial orthography methods afford an exceptionally high degree of control over stimulus properties (i.e., what is learned and how it is learned) and a participant's prior knowledge. For instance, implementing such an approach would facilitate the creation and comparison of perfectly transparent and perfectly opaque artificial orthographies. The increased methodological control equally facilitates a within-subjects design, thereby avoiding various confounding variables which historically popular between-item designs are susceptible to (e.g., Mei et al., 2014). While extensive and complex training is necessary, participants have no prior knowledge of trained artificial orthographies, cleaner manipulations are achievable, and semantic associations can be controlled. Crucially, Taylor et al. (2017) observed a strikingly similar neural response for an artificial alphabetic orthography and English reading after 10 days of training. Moreover, recently learned artificial orthographies appeared to evoke stronger neural activation compared to native languages (Taylor et al., 2013). Thus, we are confident that artificial orthography methods constitute a rigorous approach to investigating whether written and spoken language processing differences can arise solely due to the statistical structure of a writing system.

In the present study, artificial orthography methods and fMRI measures of brain activity were used to study how the orthographic transparency of a writing system impacts on reading acquisition, and on the spoken language representations that underpin reading. We tested how alphabetic and logographic writing systems differentially influence behavioural performance and the nature of emerging neural representations as adults learned to read novel words. Specifically, we assessed whether the orthographic transparency of a writing system impacts on the development of mappings between sounds, spellings, and meanings of trained words and the division of labour between dorsal and ventral pathways of the reading network (Plaut et al., 1996). Twenty-four participants were trained over 10 days on two artificial languages with alphabetic and logographic writing systems. Each language contained 24 words denoted by phonological, orthographic, and semantic components. Though highly simplified, these artificial writing systems were designed to simulate the extremes on the continuum of orthographic depth, while holding phonological and semantic properties constant (as per Smith et al., 2021). Extensive counterbalancing also reduced the possibility that any effects of the writing system could be ascribed to idiosyncratic aspects of items or to the order participants learned each language.

Learning involved completing several computerised tasks each day and performance after training was assessed using behavioural tests without feedback. Following training, neural activity was recorded using fMRI whilst participants made meaning judgements about trained spoken and written stimuli. Performance was compared using linear mixed effects models and we contrasted neural activity with voxel-wise paired-samples t-tests. In addition, we performed conjunction analyses on neural activity for spoken and written words to identify regions exhibiting speech-print convergence for each trained writing system. Finally, RSA was conducted to assess whether the nature of the writing system impacts on neural sensitivity to phonemic, orthographic, and semantic structure during reading and listening (Kriegeskorte et al., 2008). Overall, the study was designed to provide a valuable contribution to relevant questions and debates, to assist in resolving conflicting conclusions by pursuing an informed consensus, and to address gaps in the existing body of literature. Importantly, a comprehensive understanding of the processes involved in reading acquisition and possible consequences for spoken language will help inform best practices for reading instruction across different writing systems, improving levels of global literacy.

CHAPTER II: BEHAVIOURAL METHODS

2.1. The Present Study

The present study asked how the nature of the writing system impacts on reading acquisition and spoken language processing. We hypothesised that the orthographic transparency of a writing system will determine the division of labour between dorsal (orthography-phonology; O-P) and ventral (orthography-semantics; O-S) pathways of the reading network during reading aloud and comprehension (Plaut et al., 1996; Smith et al., 2021). As transparent alphabetic writing systems feature consistent, one-to-one mappings between symbols and sounds, sub-word spelling-sound information will be favoured, strengthening O-P mappings, and increasing reliance on the dorsal pathway. Equally, spoken language processing will be uniquely impacted by reading acquisition via phonological restructuring or online orthographic co-activation (Smith et al., 2021). Finally, as opaque logographic systems lack O-P systematicity (instead featuring arbitrary, whole-word mappings between spelling and sounds), O-S and the ventral pathway will be favoured as the more efficient mapping (Seidenberg, 2011).

We implemented an artificial language paradigm supported by fMRI measures of brain activity to test how alphabetic and logographic writing systems differentially influence behavioural performance and neural activation of adults learning to read novel orthographies. Twenty-four adults learned to read two sets of novel words (languages) over a two-week training period, each denoted by sounds (phonology), meanings (semantics) and unfamiliar symbols (orthographies). Figure 2.1 provides examples of trained stimuli and all stimuli presented to participants are available in the OSF storage for this project: https://osf.io/3q2jb/ (see corresponding OSF page for chapter 2).

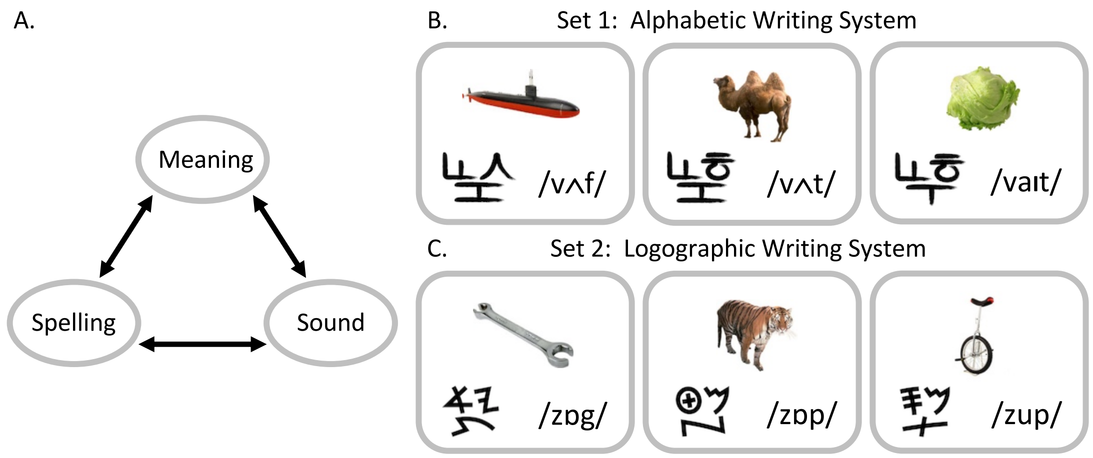


Figure 2.1. Illustration of how trained words were denoted by three associated components (A) and examples of stimuli from alphabetic (B) and logographic (C) writing systems. As the assignment of orthographies and phonologies to trained writing systems was counterbalanced across participants, this example represents the experience of six participants (see the OSF for more information).

Both trained artificial languages featured arbitrary phonology-to-semantics (P-S, sound-to-meaning) and O-S (spelling-to-meaning) mappings. However, the nature of the writing system was different for each language. The alphabetic language utilised a systematic, one-to-one relationship between O-P (spelling-to-sound), while no systematic O-P relationship existed in the logographic language. Instead, novel words in the logographic language needed to be learned as whole items. Though highly simplified, these artificial writing systems were designed to simulate the extremes on the continuum of orthographic depth, while intentionally holding phonological and semantic properties constant. Figure 2.2 illustrates how (A) transparent alphabetic and (B) opaque logographic writing systems mapped onto associated phonologies.

Behavioural performance was measured throughout the training procedure using computerised tasks (see Figure 2.3 for illustration). This procedure was informed by a pilot study conducted to examine the feasibility of preliminary training and testing protocols (see page 76). Training was structured to mimic a child's early experiences

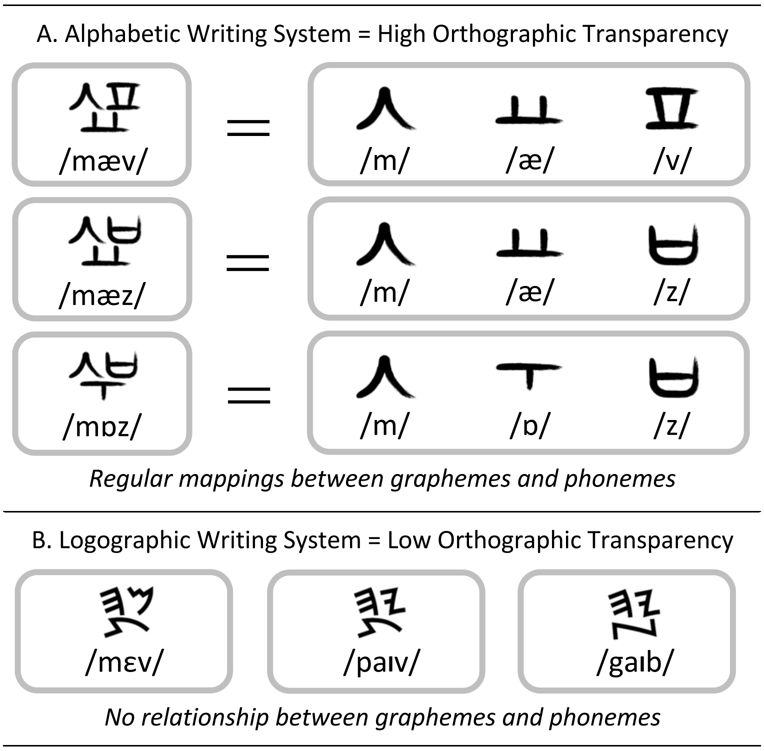


Figure 2.2. Illustration of how the transparent alphabetic writing system featured regular one-to-one mappings between graphemes and phonemes (A) while the opaque logographic system featured arbitrary whole-word mappings between spelling and sound (B).

of reading. On Day 1, we trained participants on the spoken forms of novel words and their meanings, after first taking background measures of spelling and vocabulary ability (Figure 2.3, row A). Then, on Day 2, we exposed them for the first time to the new orthographic forms and their relationship to the sounds and meanings of the novel words (Figure 2.3, row B). Phonology-to-semantics, orthography-to-phonology, and orthography-to-semantics mappings were trained over the remaining days of a two-week procedure (Figure 2.3, row C). Following training, participants completed behavioural tests to assess learning (Figure 2.3, row D) and were asked to monitor the meanings of trained spoken and written pseudowords while neural responses were recorded using fMRI (Day 11 and 13; see Chapter 4 for more details). Brain imaging

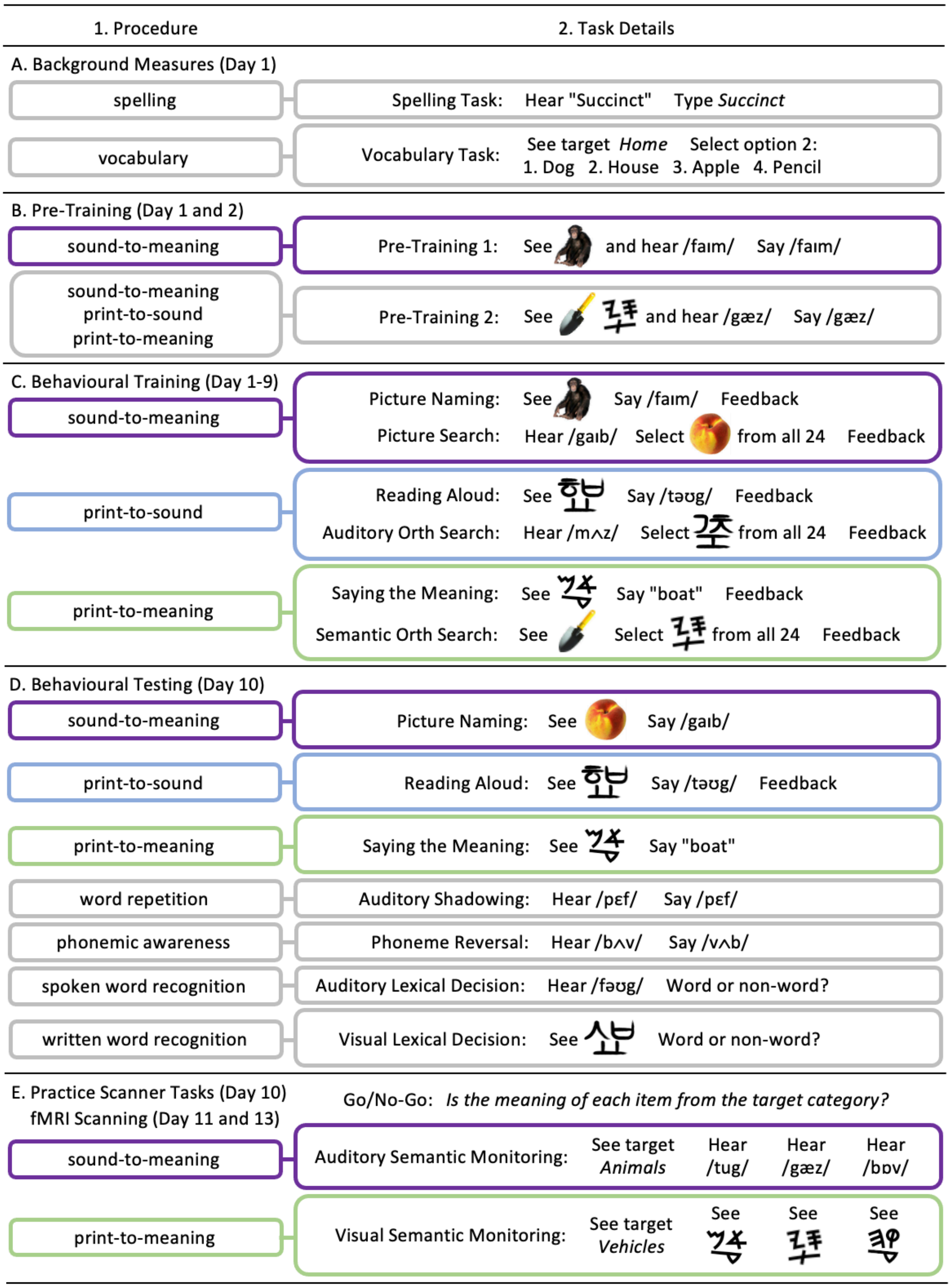


Figure 2.3. Summary of training, testing, and scanning procedures. Column 1 outlines the focus of each procedure and when it was conducted. Column 2 includes specific details about associated tasks.

was used to evaluate whether the nature of the writing system differentially impacted the reading network during reading comprehension and spoken word processing.

To begin, details about the participants are provided before elaborating on the characteristics of all stimuli associated with trained artificial languages (i.e., spoken pseudoword forms, artificial orthographies, and word meanings). Next, the procedure (including training and testing protocols) is outlined before describing the pilot study and the associated procedure, results, and conclusions. All materials, data and analysis scripts can be found in the OSF storage for this project: https://osf.io/3q2jb/.

2.2. Participants

Twenty-four monolingual native English-speaking adults (16 females) aged 19-35 (*M* = 22.16, *SD* = 3.97) participated in the experiment. All participants were right-handed, with no history of hearing impairment, uncorrected visual impairment, or learning difficulties. Participants worked or studied at Royal Holloway, University of London, United Kingdom (RHUL). A screening checklist was completed by all participants to assess exclusion criteria and safety requirements for MRI scanning (see OSF). Participants were paid 150.00 GBP for their participation in the study. One additional female adult aged 22 participated in a pilot study and was paid 70.00 GBP. Ethical approval was granted by the University Research Ethics Committee at RHUL.

2.3. Stimuli

Spoken pseudoword forms

Eight consonants (/b/, /f/, /g/, /m/, /p/, /t/, /v/, /z/) and eight vowel sounds (phonemes; /ɛ/, /ʌ/, /aɪ/, /əʊ/, /æ/, /ɒ/, /i/, /u/) were used to create two sets of 24 monosyllabic consonant-vowel-consonant (CVC) pseudowords (phonologies). Each participant learned both sets of spoken words. In order to reduce their confusability, the two sets of phonologies featured different vowel sounds (as per Taylor, Davis & Rastle, 2017; see Figure 2.1 for examples of spoken pseudowords). Four vowels were used to create one phonology (phonology 1: /ɛ/, /ʌ/, /aɪ/, /əʊ/); four were used to create the other (phonology 2: /æ/, /ɒ/, /i/, /u/). Thus, each phonology contained two short vowels (/ɛ/, /ʌ/ and /æ/, /ɒ/) and two diphthongs (combinations of two vowel sounds; /aɪ/ and /əʊ/) or long vowels (/i/ and /u/). Within each phonology, vowels featured within six items and consonants occurred three times in onset position (the first phoneme) and three times in coda position (the final phoneme). Each spoken pseudoword also shared both consonants with one pseudoword from the other phonology (e.g., phonology 1 bʌv, phonology 2 bæv). Two further sets of 48 monosyllabic CVC pseudowords (auditory distractors) were created using the phonologies. These sets of spoken pseudowords were used to test recognition of trained items. Within each set of auditory distractors, untrained pseudowords were created by replacing one consonant or vowel from a trained pseudoword with an alternative from the same phonology. All spoken pseudowords were recorded by a female native English speaker and digitised at a sampling rate of 44.1 kHz. The OSF includes all stimuli presented to participants.

Artificial orthographies

Two sets of 12 symbols were selected from one modern and one archaic orthography: Korean Hangul and Phoenician. Each phoneme used to create the two phonologies was associated with one symbol (grapheme) from each set (i.e., /ɛ/ was associated with one Korean Hangul grapheme and one Phoenician grapheme). We created two sets of 24 written pseudowords that operated alphabetically by associating each phoneme with one symbol from each script in a one-to-one manner for each phonology (as per Taylor et al., 2017). Similarly, we created two sets of 24 written pseudowords that operated logographically by removing all systematicity between sounds and symbols. Figure 2.2 demonstrates how trained languages operated using different writing systems. Each participant learned one phonology written in Korean Hangul and the other written in Phoenician. Within each orthography, symbols associated with each pseudoword were arranged as a triangle (as per Mei et al., 2014; see Figure 2.1 for examples). Finally, two further sets of 48 written pseudowords (visual distractors) were created using the two sets of 48 auditory distractors and the same regular, one-to-one mapping between sounds and symbols used to construct both orthographies. These sets of pseudowords were used to test recognition of trained written items.

Word meanings

Two sets of 24 semantic objects (meanings) were created using six animals, six fruits or vegetables, six tools, and six vehicles. All were familiar to participants. A picture of each meaning was selected from the Hemera Photo Objects 50,000 Premium Image Collection or the internet ($n = 3$) if necessary and assigned a single word name. Many of these meanings were used in experiments conducted by Tyler et al. (2003) and Taylor et al. (2017). Figure 2.1 includes examples of semantic objects associated with trained items. The MRC Psycholinguistic database (Max Coltheart, 1981) was used to match the two sets of meanings based on familiarity (as per Taylor et al., 2017).

Counterbalancing

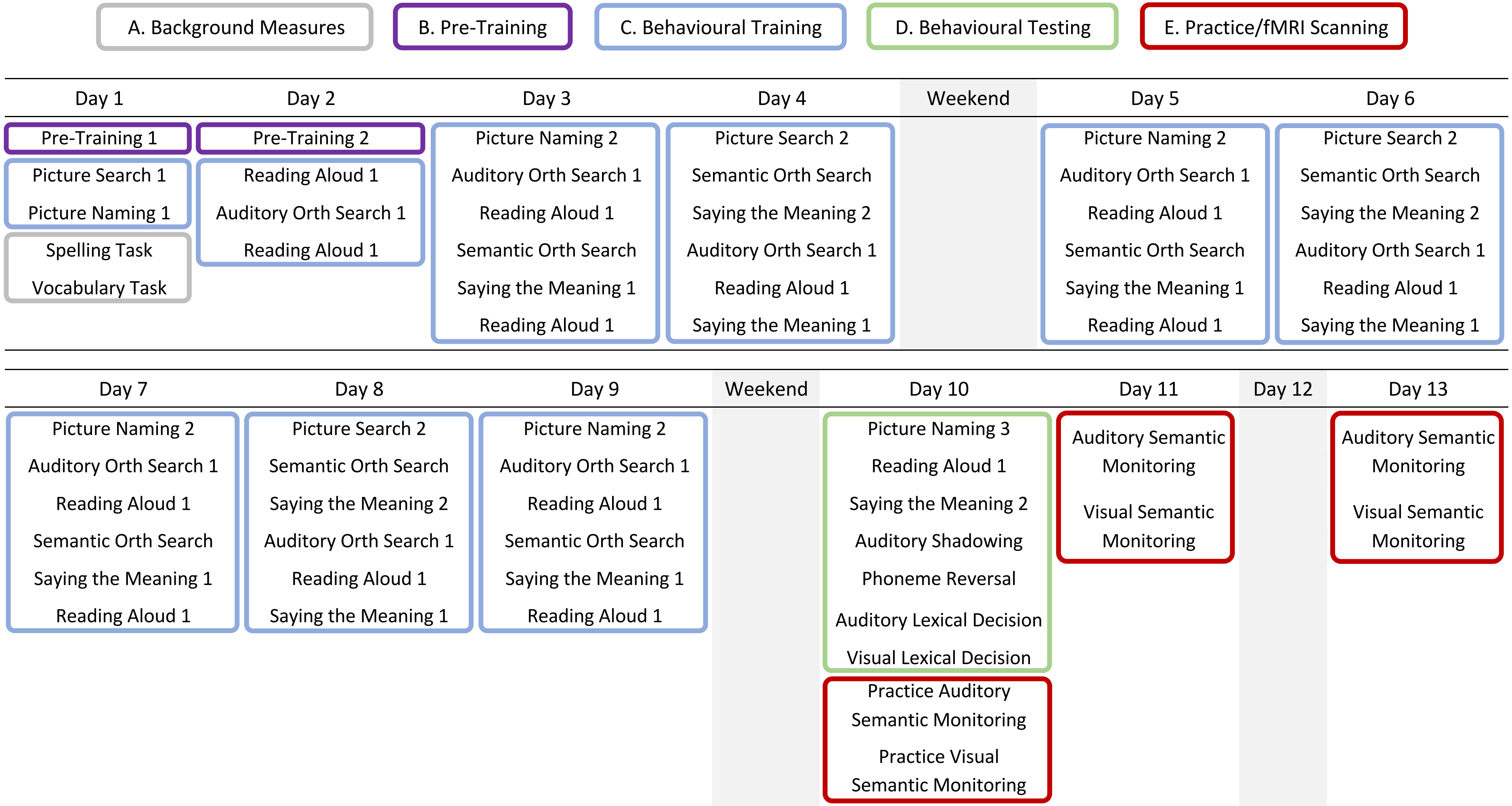
One virtue of artificial orthography paradigms is that it is possible to exercise a very high degree of control over stimulus properties. Twenty-four participants learned to read two novel languages, one with an alphabetic and one with a logographic writing system. This study did not counterbalance to assignment of semantic objects: one set was associated with the alphabetic system, while the other featured in the logographic system. Within both sets of semantic objects, meanings were randomly assigned to spoken and written pseudowords to avoid systematicity between semantic category and sound or spelling. However, the assignment of phonology and orthographic script was counterbalanced across participants. Finally, the order in which participants were trained and tested on their knowledge of the writings systems was counterbalanced to avoid order effects; 12 participants performed tasks focusing on the alphabetic writing system first, 12 began with tasks focusing on the logographic system. This extensive counterbalancing is important as it reduces the possibility that any effects of writing system can be ascribed to idiosyncratic aspects of items or to the order participants learned each artificial language. The OSF provides full details about counterbalancing.

2.4. Procedure

The procedure was designed to ensure all participants could successfully learn to read two artificial languages with alphabetic and logographic writing systems. Participants were trained and tested over a three-week period using computerised tasks (see Figure 2.4 for a summary of the procedure). Sessions on each day lasted for approximately 1.5 hours and all tasks were self-paced. Items from both writing systems were presented in separate runs of each task and performance was assessed throughout.

Background measures (see Figure 2.3, row A)

Individual differences in spelling and vocabulary skill were measured before participants learned the two artificial languages. To measure spelling ability, we presented participants with a subset of English words taken from Burt & Tate (2002). All words were 8-10 letters long, low-frequency, and had no orthographic neighbours. The words had a mean bigram frequency of 340 (*SD* = 167) and mean CELEX frequency of 1.6 (*SD* = 1.2). Forty words were presented during one block of 40 trials in a set order. On each trial, participants heard one word independently and then within a sentence before typing the word and pressing the space bar to continue. To measure vocabulary knowledge, we used a test from Shipley (1940) involving 40 trials in a set order. Each trial included five words; one target and four options labelled 1-4. On each trial, participants typed the number corresponding to the word that shared its meaning with the target (e.g., 'Home' and 'House' as opposed to 'Dog', 'Apple' or 'Pencil'). The OSF contains all stimuli presented during spelling and vocabulary tasks.



A. Background Measures | B. Pre-Training | C. Behavioural Training | D. Behavioural Testing | E. Practice/fMRI Scanning

Day 1	Day 2	Day 3	Day 4	Weekend	Day 5	Day 6
Pre-Training 1 Picture Search 1 Picture Naming 1 Spelling Task Vocabulary Task	Pre-Training 2 Reading Aloud 1 Auditory Orth Search 1 Reading Aloud 1	Picture Naming 2 Auditory Orth Search 1 Reading Aloud 1 Semantic Orth Search Saying the Meaning 1 Reading Aloud 1	Picture Search 2 Semantic Orth Search Saying the Meaning 2 Auditory Orth Search 1 Reading Aloud 1 Saying the Meaning 1		Picture Naming 2 Auditory Orth Search 1 Reading Aloud 1 Semantic Orth Search Saying the Meaning 1 Reading Aloud 1	Picture Search 2 Semantic Orth Search Saying the Meaning 2 Auditory Orth Search 1 Reading Aloud 1 Saying the Meaning 1

Day 7	Day 8	Day 9	Weekend	Day 10	Day 11	Day 12	Day 13
Picture Naming 2 Auditory Orth Search 1 Reading Aloud 1 Semantic Orth Search Saying the Meaning 1 Reading Aloud 1	Picture Search 2 Semantic Orth Search Saying the Meaning 2 Auditory Orth Search 1 Reading Aloud 1 Saying the Meaning 1	Picture Naming 2 Auditory Orth Search 1 Reading Aloud 1 Semantic Orth Search Saying the Meaning 1 Reading Aloud 1		Picture Naming 3 Reading Aloud 1 Saying the Meaning 2 Auditory Shadowing Phoneme Reversal Auditory Lexical Decision Visual Lexical Decision Practice Auditory Semantic Monitoring Practice Visual Semantic Monitoring	Auditory Semantic Monitoring Visual Semantic Monitoring		Auditory Semantic Monitoring Visual Semantic Monitoring

Figure 2.4. Summary of the main study procedure including the tasks performed on each day. Procedures A-E correspond to those described in Figure 2.3. Note that tasks associated with all procedures other than Background Measures (A) and Practice/fMRI Scanning (E) were repeated for both trained writing systems on each day.

Sound-to-meaning pre-training (see Figure 2.3, row B)

Before learning to read two artificial orthographies, participants were exposed to sounds and meanings from both languages on Day 1. Slides were used to explain how phonological and semantic stimuli operated; each spoken pseudoword had three phonemes and an arbitrary association with a meaning from one of four categories (see OSF). Participants began learning relationships between the spoken forms of 24 pseudowords and their meanings from each language with a repetition task (*Pre-Training 1*). Three blocks of 24 trials each presented all spoken pseudowords and pictures of their meanings once in a randomised order. During each trial, participants looked at the picture and repeated its associated spoken pseudoword aloud within nine seconds before pressing the space bar to continue. No feedback was provided.

Spelling-to-sound and spelling-to-meaning pre-training (see Figure 2.3, row B)

Spellings of spoken pseudowords from both writing systems were introduced on Day 2. First, slides were used to explain how pseudowords written in unfamiliar orthographic scripts operated alphabetically and logographically without explicitly stating the relationship between trained stimuli (see OSF). The slides explained that alphabetic writing systems exhibit systematic one-to-one mappings between their sounds and symbols while no relationship exists between the sounds and written words comprising logographic writing systems. Next, a repetition task was similarly used to introduce trained stimuli and familiarise participants with associations between the spoken forms, written forms, and meanings of the 24 pseudowords from each writing system (*Pre-Training 2*). On each trial, participants saw the written form of a trained pseudoword, heard its pronunciation, and saw a picture of an associated meaning.

Behavioural training (see Figure 2.3, row C)

Participants continued learning the artificial writing systems for seven working days (Day 3-9). Six tasks were completed on each day to encourage engagement and reduce boredom and fatigue. On Day 3, participants performed one task focusing on sound-to-meaning (P-S) mappings, three on spelling-to-sound (O-P) mappings, and two on spelling-to-meaning (O-S) mappings. On Day 4, participants performed a different task focusing on P-S mappings, two on O-P mappings, and three on O-S mappings. The Day 3 and Day 4 procedures were then alternated on Days 5 to 9. Tasks either required a verbal response (response tasks) or for participants to choose from all 24 written pseudowords or semantic objects (search tasks). Some tasks had multiple versions that included a different number of trials and whether feedback was provided but were otherwise identical. Crucially, the training procedure was identical for both writing systems. E-Prime (Version 2.0; Psychology Software Tools, 2003) recorded verbal responses and accuracy and response time (RT) for tasks that required the participant to respond using a keyboard or mouse. Accuracy and RT of verbal responses were coded offline through manual inspection of the speech waveform using CheckFiles (a variant of CheckVocal; Version 2.3.1; Protopapas, 2007).

P-S tasks

The following tasks focused on the relationship between phonology and semantics and involved mapping sounds to meanings from trained languages. Note that participants also performed Picture Naming 1 and Picture Search 1 on Day 1 after the repetition task (*Pre-Training 1*) to support initial learning of sound-to-meaning mappings.

Picture Naming

All semantic objects from one trained language were presented in a randomised order during three blocks of 24 trials (*Picture Naming 1*). On each trial, participants saw a picture of an object on the screen and had to say the associated spoken pseudoword aloud within nine seconds. They then pressed the space bar to hear the correct response. A second version of the task (*Picture Naming 2*) included only one block.

Picture Search

All spoken pseudowords from one language were presented in a randomised order during three blocks of 24 trials (*Picture Search 1*). On each trial, participants heard one pseudoword and saw all semantic objects from the same language in a four x six grid. Participants then selected the associated meaning using the mouse and the correct answer was circled. Semantic objects featured in different locations within the four x six array for each block of trials. *Picture Search 2* included only one block.

O-S tasks

The following tasks focused on the relationship between orthography and phonology and required participants to associate written and spoken pseudowords from trained writing systems. Participants also performed these tasks on Day 2 after the repetition task (*Pre-Training 2*) to support initial learning of spelling-to-sound mappings.

Reading Aloud 1

All written pseudowords from one writing system were presented in a randomised order during three blocks of 24 trials. On each trial, participants said the pronunciation of the written pseudoword aloud within nine seconds then pressed the space bar to hear the correct response. One version of the task was used during the main procedure.

Auditory Orthographic Search 1

All spoken pseudowords from one trained writing system were presented in a randomised order during one block of 24 trials. On each trial, participants heard one pseudoword and saw all written pseudowords from the same writing system presented in a four x six grid. Participants then selected the associated written pseudoword using the mouse before the correct answer was circled to provide feedback. Written pseudowords were in the same location within the four x six array on every trial.

O-S tasks

The following tasks focused on the relationship between orthography and semantics and involved mapping between written pseudowords and associated meanings.

Saying the Meaning 1

All written pseudowords from one writing system were presented in a randomised order across three blocks of 24 trials. On each trial, participants said the meaning of the written word aloud in English (as opposed to its pronunciation in the new language) within nine seconds and pressed the space bar to hear the correct response.

Semantic Orthographic Search

All semantic objects from one trained writing system were displayed individually in a randomised order during one block of 24 trials. On each trial, participants saw one semantic object at the top of the screen and all written pseudowords from the same writing system displayed underneath in a four x six grid. Participants then selected the written pseudoword associated with the presented semantic object using the mouse before the correct answer was circled to provide feedback. Written pseudowords were presented in the same location within the four x six grid on every trial.

Behavioural testing (see Figure 2.3, row D)

Following training (Day 10), participants completed various computerised tests to assess their knowledge of trained writing systems. Reading Aloud 1 was conducted to assess learning but continued to provide feedback to encourage recollection of trained items following a break for the second weekend. A third version of Picture Naming (*Picture Naming 3*) and a second version of Saying the Meaning (*Saying the Meaning 2*) presented all spoken and written pseudowords from one trained writing system during one block of 24 trials; however, there was no time-limit to respond, and no feedback was provided. Participants additionally completed the following tests.

Auditory Shadowing

All spoken pseudowords from one trained language were presented in a randomised order across 24 trials. On each trial, participants focused on a fixation cross, listened to and repeated the spoken pseudoword before pressing the space bar to continue. This behavioural test investigated an orthographic effect on spoken word processing.

Phoneme Reversal

All spoken pseudowords from one trained language were presented in a randomised order across 24 trials. During each trial, participants focused on a fixation cross and repeated the CVC pseudoword while swapping the consonants in onset and coda position (e.g., /bɛv/ should be repeated as /vɛb/) before pressing the space bar to continue. This test investigated an orthographic effect on phonemic awareness.

Lexical Decision

All trained spoken pseudowords from one artificial language and one set of untrained auditory distractors were presented in a randomised order during one block of 96 trials (*Auditory Lexical Decision*). Twenty-four trained spoken pseudowords were presented twice, 48 auditory distractors were presented once. On each trial, participants pressed Z on the keyboard if they had learned the item and M if they had not. This tested recognition of whole-word forms of trained spoken pseudowords. A second version of the task (*Visual Lexical Decision*) presented all written pseudowords from one writing system and an associated set of visual distractors but was otherwise identical.

fMRI scanning (see Figure 2.3, row E)

Following behavioural testing, participants completed tasks on Day 10 to prepare them for fMRI scanning on Day 11 and 13. All spoken pseudowords from both trained languages were presented in a randomised order during eight blocks of six trials (*Practice Auditory Semantic Monitoring*). Blocks 1-4 presented stimuli from one language and Blocks 5-8 presented stimuli from the other language. A target semantic category (animals, fruit or vegetables, tools, or vehicles) was displayed at the beginning of each block. All categories were presented twice in a randomised order, once during block 1-4 and again during block 5-8. On each trial, participants pressed the space bar on the keyboard within three seconds if the meaning of the spoken pseudoword (e.g., pencil) matched the target semantic category (e.g., tools). At the end of Block 4, participants received simple feedback to encourage participants to keep trying; “Well Done! It looks like you're concentrating on the task” if they responded during any trial or “Oops! Try and concentrate! You didn't respond to any of the trials”. A second version of the task (*Practice Visual Semantic Monitoring*) presented all written pseudowords from both trained writing systems but was otherwise identical.

On Day 11 and 13, participants monitored the meanings of spoken and written stimuli while neural responses were recorded using fMRI. All spoken pseudowords from both trained languages were presented four times in a randomised order during 12 blocks of 16 trials (*Auditory Semantic Monitoring*). Each block presented stimuli from one language which alternated between blocks. A target semantic category was displayed at the beginning of each block and all categories were presented three times in a randomised order. On each trial, participants pressed a button within three seconds if the meaning of the spoken pseudoword matched the target semantic category. At the end of every third block, participants received the same simple feedback they were presented with during the practice version of this task to encourage participants to keep trying. A second version of the task (*Visual Semantic Monitoring*) presented all written pseudowords from both writing systems but was otherwise identical.

Counterbalancing was implemented to reduce the possibility that any effects of writing system could be ascribed to the order in which participants were tested on their knowledge of each writing system, or whether they first monitored the meanings of spoken or written pseudowords during fMRI scanning. Semantic monitoring tasks presented pseudowords from both trained writing systems in a manner that alternated between multiple blocks. Accordingly, 12 participants began with pseudowords from the alphabetic system; 12 began with logographic pseudowords. In addition, 12 participants performed Auditory Semantic Monitoring first; 12 began with Visual Semantic Monitoring. The OSF provides full details about counterbalancing.

2.5. Pilot Study

A pilot study was conducted to investigate how effectively one participant could learn two artificial languages with alphabetic and logographic writing systems over a five-day procedure. It was intended to inform refinements to the main study procedure to ensure all participants could successfully learn to read both writing systems. Methods and results of the pilot study are available on the OSF. Overall, the pilot study indicated that sufficient learning of trained alphabetic and logographic writing systems was not possible during a five-day procedure. For the alphabetic system, O-P mappings were acquired more easily than P-S and O-S mappings. O-P performance was 79%, P-S performance was 63%, and O-S performance was 60%. In contrast, for the logographic writing system, P-S mappings were acquired more easily than O-P and O-S mappings. P-S performance was 63%, O-P performance was 33%, and O-S performance was 22%. As the pilot participant did not successfully learn all sound-to-meaning, spelling-to-sound, and spelling-to-meaning mappings associated with both writing systems, we decided to extend the training procedure from two to seven days for the main study (see Figure 2.4 for a summary of the main study procedure). In addition, minor refinements were made to procedure for the main study to encourage learning.

CHAPTER III: BEHAVIOURAL RESULTS

The present study asked how the orthographic transparency of a writing system impacts on spoken language and reading acquisition. Participants learned to read two artificial languages with alphabetic and logographic writing systems over a two-week period (see Figure 2.4 in chapter 2 for more information). We trained participants on phonology-to-semantics (P-S, sound-to-meaning), orthography-to-phonology (O-P, spelling-to-sound), and orthography-to-semantics (O-S, spelling-to-meaning) mappings using computerised tasks. Following training, participants completed behavioural tests to assess learning and were asked to monitor the meanings of trained spoken and written pseudowords while neural responses were recorded using fMRI. E-Prime recorded verbal responses as well as accuracy and response time (RT) for button-press tasks. Accuracy and RT of verbal responses were coded offline through manual inspection of the speech waveform using CheckFiles (a variant of CheckVocal; Version 2.3.1; Protopapas, 2007). To present our results graphically, RT was calculated as the average response time across all correct trials while accuracy was calculated as the proportion of trials answered correctly (number of correct responses / total number of trials). No participants were removed from any analyses as performance was consistently high. All materials, data and analysis scripts can be found in the OSF storage for this project: https://osf.io/3q2jb/.

3.1. Background Measures

Performance (accuracy) on tasks evaluating spelling and vocabulary skills were included as covariates during neuroimaging data analysis (see chapter 4 for more information). 24 participants performed 40 trials on the spelling task and 40 trials on the vocabulary task. Figure 3.1 shows accuracy for each participant on the spelling task; Figure 3.2 shows accuracy for each participant on the vocabulary task.

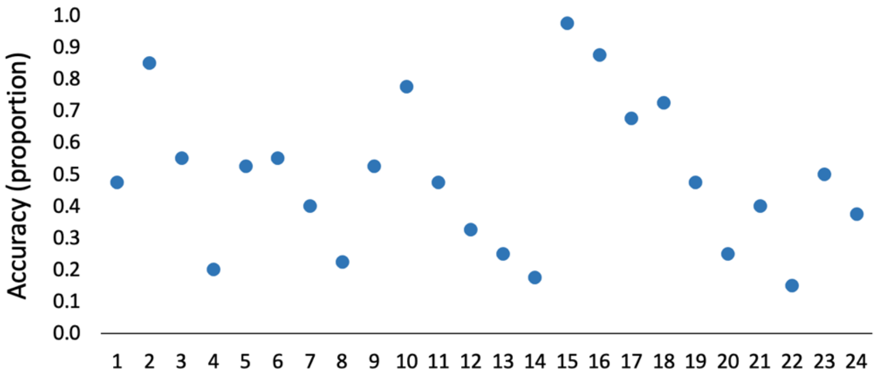


Figure 3.1. Accuracy on the Spelling Task for Each Participant

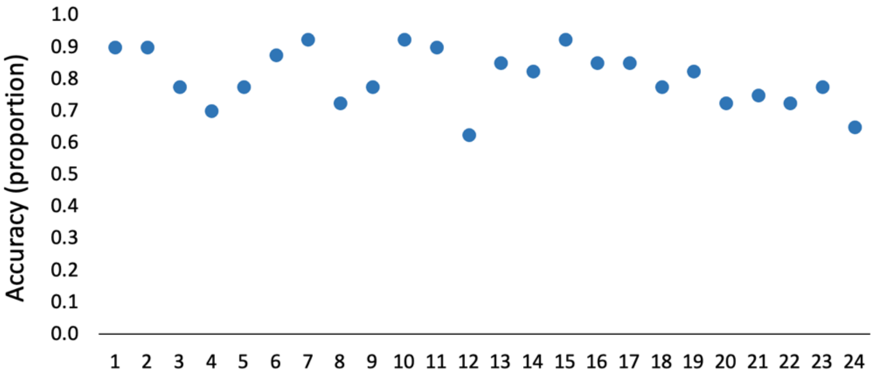


Figure 3.2. Accuracy on the Vocabulary Task for Each Participant

3.2. Performance During Training

Linear Mixed-Effects Models (LME) were constructed to assess performance on six training tasks as a function of the fixed factors Writing System and Day. Different analyses included data from varying training days as participants performed each task on different occasions during the procedure (see Figure 2.4 in chapter 2). Day was mean-centred (c), as continuous fixed factors should be standardised to manage collinearity, and to benefit the interpretation of resulting coefficients (Meteyard & Davies, 2019). Accuracy and RT were modelled using Binomial (logistic) and Poisson (linear) distributions, respectively, within the lme4 package (Version 1.1-12, Bates, Mächler, Bolker, & Walker, 2015) in R (Version 3.6.0; R Core Team, 2019). RT data were log transformed to reduce distribution skewing. All datapoints were included in accuracy analyses while RT analyses only included correct responses. No outliers were removed. LME models included participant and semantic object as random factors. However, for RT analysis of Semantic Orthographic Search, semantic object was removed as a random factor to simplify the model and resolve convergence issues (Matuschek, Kliegl, Vasishth, Baayen, & Bates, 2017). Spoken and written pseudowords were not included as random factors as they were fully counterbalanced, neutralising random effects they may have otherwise exerted. The random effects structure specified intercepts only. Finally, to help us interpret the results of our LME models, we specified contrasts for the fixed factor Writing System to ensure that resulting values for intercept and fixed effects corresponded to the grand mean and main effects, respectively. Model equations were as follows:

Accuracy: glmer(Acc ~ WritingSystem*cDay + (1|Subject) + (1|Sem), data=results, family=binomial)

RT: lmer(logRT ~ WritingSystem*cDay + (1|Subject) + (1|Sem), data=correct)

Beta ($\hat{\beta}$), odds ratio (OR), standard error (SE), *Z*, and *p* values are reported for LME models analysing accuracy data. $\hat{\beta}$, SE, *t* and *p* values are reported for RT models. $\hat{\beta}$ is the fixed effect coefficient (the estimated difference between conditions having controlled for random effects) and is logit transformed for accuracy models. OR is derived from $\hat{\beta}$ and is the log transformed ratio of the probability of responding accurately for the alphabetic condition over the probability of responding accurately for the logographic condition. Test statistics Z and t denote the estimated effect size having accounted for random effects and variability in the dataset (i.e., SE). Z is reported for general linear models as they do not assume the dependent variable (DV) is normally distributed (i.e., binomial accuracy data). t is reported for linear models as they assume the DV is normally distributed (i.e., continuous RT data).

Picture naming

24 participants performed 72 trials per Writing System on Day 1, followed by 24 trials per Writing System on Days 3, 5, 7, and 9, totalling 8,064 data points. Figure 3.3A shows average accuracy for alphabetic and logographic conditions on each day the task was performed. There was a main effect of Day, as accuracy increased during training, $\hat{\beta} = .32$, OR = 1.38, $SE = .01$, $Z = 26.63$, $p < .001$, but no main effect of Writing System, $\hat{\beta} = -.12$, OR = .89, $SE = .27$, $Z = -.45$, $p = .655$. However, there was an interaction between Writing System and Day, $\hat{\beta} = -.06$, OR = .95, $SE = .02$, $Z = -2.38$, $p = .018$, indicating that performance improved faster for the alphabetic condition, while it converged for the two writing systems by the end of training. Figure 3.3B shows average RT for alphabetic and logographic conditions on the same training days. There was a main effect of Day, as RT decreased during the training procedure, $\hat{\beta} = -.06$, $SE = .00$, $t = -28.44$, $p < .001$. However, there was no main effect of Writing System, $\hat{\beta} = .04$, $SE = .04$, $t = .91$, $p = .366$, and no interaction between Writing System and Day, $\hat{\beta} = .01$, $SE = .00$, $t = 1.33$, $p = .182$. Notably,

participants were more accurate and faster on Day 1 than Day 3. This is likely because they performed Picture Naming after sound-to-meaning Pre-Training (see Figure 2.3, row B in chapter 2) on Day 1, and no P-S tasks on Day 2, before performing Picture Naming at the beginning of Day 3 (see Figure 2.4, chapter 2).

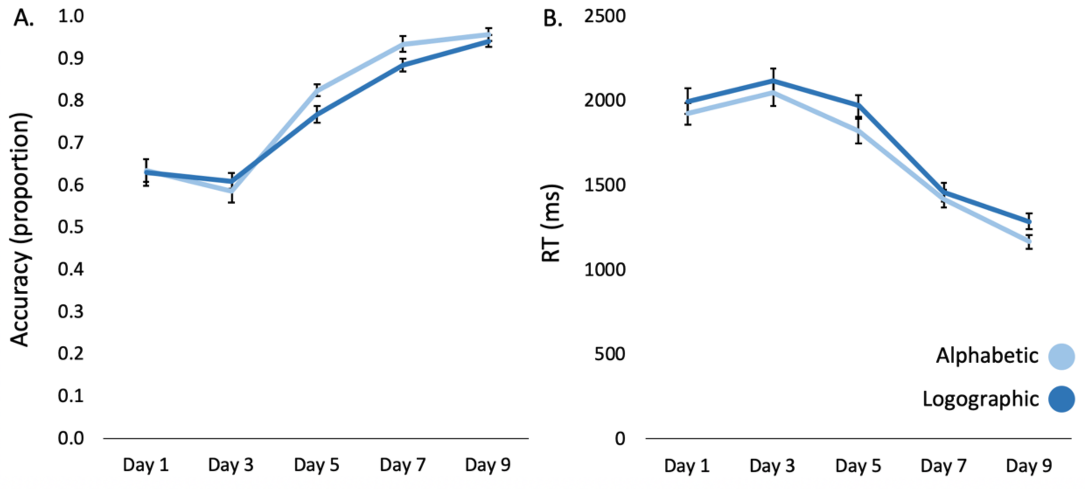


Figure 3.3. Accuracy and Average RT on Picture Naming During Training

Note. Accuracy (A) and average RT (B) on Picture Naming for alphabetic and logographic conditions over five training days. Error bars denote within-subjects SE.

Picture search

24 participants performed 72 trials per Writing System on Day 1, followed by 24 trials per Writing System on Days 4, 6, and 8, totalling 6,912 data points. Figure 3.4A shows average accuracy for alphabetic and logographic conditions on each day the task was performed. There was a main effect of Day, as accuracy increased during training, $\hat{\beta} = .53$, OR = 1.70, $SE = .02$, $Z = 26.22$, $p < .001$, but no main effect of Writing System, $\hat{\beta} = -.33$, OR = .72, $SE = .22$, $Z = -1.51$, $p = .130$. However, there was an interaction between Writing System and Day, $\hat{\beta} = -.17$, OR = .85, $SE = .04$, $Z = -4.15$, $p < .001$, indicating that performance improved more

quickly for the alphabetic system, while it converged by the end of training for the two writing systems. Figure 3.4B shows average RT for alphabetic and logographic conditions on the same training days. There was a main effect of Day, as RT decreased during training, $\hat{\beta} = -.06$, $SE = .00$, $Z = -21.11$, $p < .001$. However, there was no main effect of Writing System, $\hat{\beta} = .05$, $SE = .05$, $t = 1.01$, $p = .317$, nor an interaction between Writing System and Day, $\hat{\beta} = .01$, $SE = .01$, $t = 1.87$, $p = .062$.

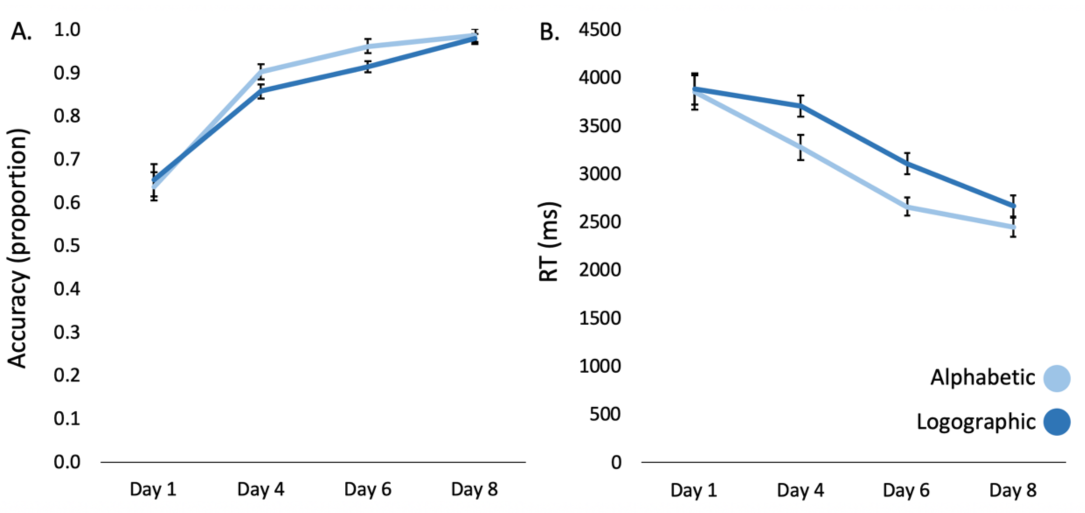


Figure 3.4. Accuracy and Average RT on Picture Search During Training

Note. Accuracy (A) and average RT (B) on Picture Search for alphabetic and logographic conditions over four training days. Error bars denote within-subjects SE.

Reading aloud

24 participants performed 144 trials per Writing System on Days 2, 3, 5, 7, and 9, and 72 trials per Writing System on Days 4, 6, and 8. Scoring each of the resulting 44,928 data points for accuracy and RT was judged to be unfeasible, given that this involved manual coding of vocal responses. Thus, the final 24 trials from each Writing System and Day were sampled, yielding 9,216 data points. Figure 3.5A shows average accuracy for alphabetic and logographic conditions on each day the

task was performed. There were main effects of Day and Writing System, as accuracy increased during training, $\hat{\beta} = .56$, OR = 1.74, *SE* = .03, $Z = 20.89$, $p < .001$, and was higher for the alphabetic condition, $\hat{\beta} = -2.23$, OR = .11, *SE* = .22, $Z = -10.02$, $p < .001$. The main effect of Writing System was qualified by an interaction with Day, $\hat{\beta} = .34$, OR = 1.40, *SE* = .05, $Z = 6.37$, $p < .001$, reflecting the fact that performance for the alphabetic writing system was already at ceiling early in training while performance on the logographic writing system continued to improve throughout the training period. Figure 3.5B shows average RT for alphabetic and logographic conditions on the same training days. There were main effects of Day and Writing system, as RT decreased during training, $\hat{\beta} = -.11$, *SE* = .00, $t = -53.12$, $p < .001$, and was faster for the alphabetic condition, $\hat{\beta} = .11$, *SE* = .03, $t = 3.91$, $p < .001$. Finally, there was an interaction between Writing System and Day, $\hat{\beta} = .02$, *SE* = .00, $t = 3.76$, $p < .001$, as improvement in RT was greater for the alphabetic writing system compared to the logographic writing system.

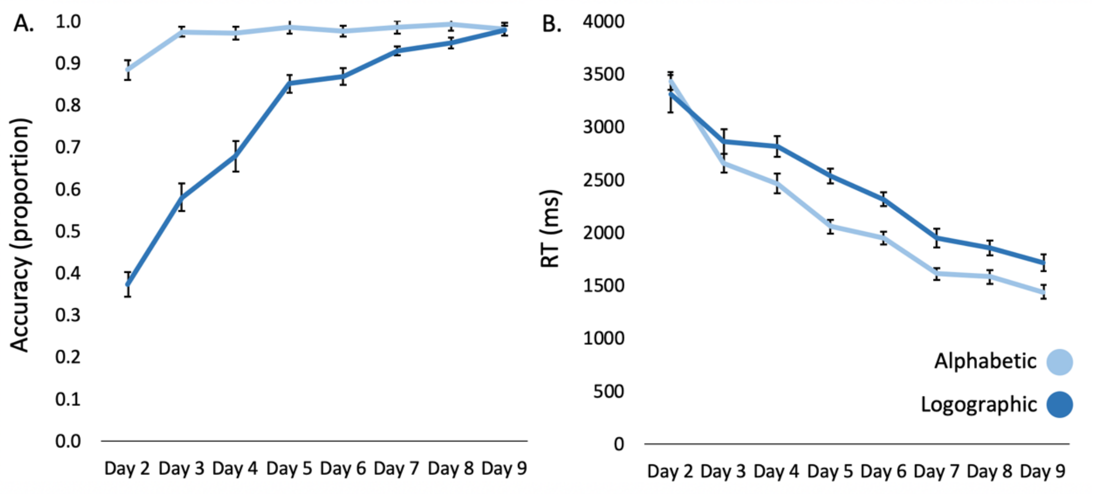


Figure 3.5. Accuracy and Average RT on Reading Aloud During Training

Note. Accuracy (A) and average RT (B) on Reading Aloud for alphabetic and logographic conditions over eight training days. Averages were calculated from the final 24 trials sampled from each Writing System and Day. Error bars denote within-subjects SE.

Auditory orthographic search

24 participants performed 24 trials per Writing System on Days 2-9, totalling 9,216 data points. Figure 3.6A shows average accuracy for alphabetic and logographic conditions on each day the task was performed. There were main effects of Day and Writing System, as accuracy increased during training, $\hat{\beta} = .66$, OR = 1.94, $SE = .03$, $Z = 25.03$, $p < .001$, and was higher for the alphabetic condition, $\hat{\beta} = -2.85$, OR = .06, $SE = .22$, $Z = -13.07$, $p < .001$. The main effect of Writing System was qualified by an interaction with Day, $\hat{\beta} = .22$, OR = 1.25, $SE = .05$, $Z = 4.29$, $p < .001$, reflecting that performance was near ceiling for the alphabetic writing system from early in training. Figure 3.6B shows average RT for alphabetic and logographic conditions on the same training days. There were main effects of Day and Writing System, as RT decreased during training, $\hat{\beta} = -.10$, $SE = .00$, $t = -30.47$, $p < .001$, and was faster for the logographic writing system, $\hat{\beta} = -.12$, $SE = .05$, $t = -2.46$, $p = .018$. Finally, there was an interaction between Writing System and Day, $\hat{\beta} = -.02$, $SE = .00$, $t = -2.33$, $p = .020$. This interaction reflects more rapid responding in the logographic writing system early in training; however, it is important to note that because accuracy for the logographic system was so poor at this point in training, only very few data points contribute to the RT analysis for that writing system.

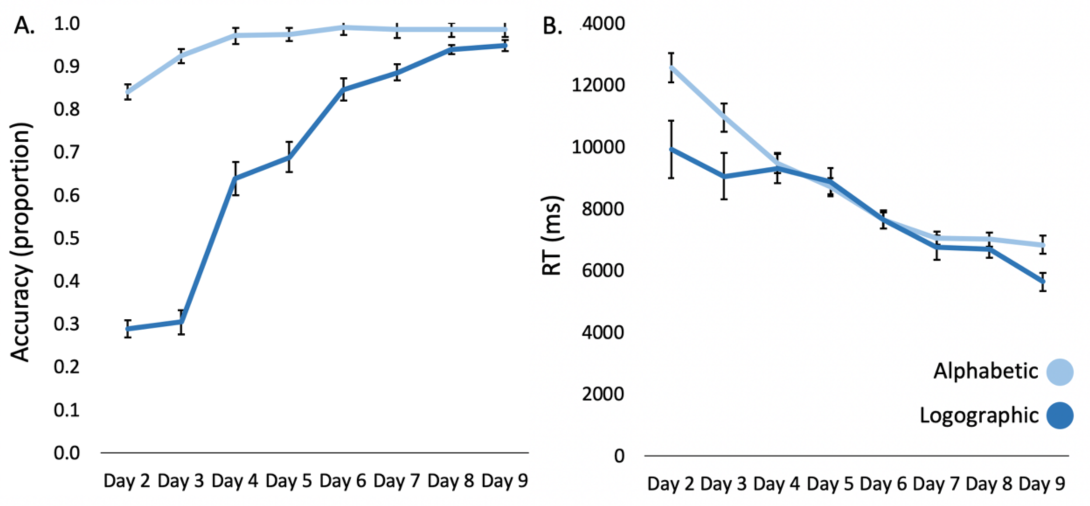


Figure 3.6. Accuracy and Average RT on Auditory Orthographic Search During Training

Note. Accuracy (A) and average RT (B) on Auditory Orthographic Search for alphabetic and logographic conditions over eight training days. Error bars denote within-subjects SE.

Saying the meaning

24 participants performed 72 trials per Writing System on Days 3, 5, 7, and 9, and 144 trials per Writing System on Days 4, 6, and 8. Scoring each of the resulting 34,560 data points for accuracy and RT was judged to be unfeasible, given that this involved manual coding of vocal responses. Thus, the final 24 trials from each Writing System and Day were sampled, yielding 8,064 data points. Figure 3.7A shows average accuracy for alphabetic and logographic conditions on each day the task was performed. There were main effects of Day and Writing System, as accuracy increased during training, $\hat{\beta} = .68$, OR = 1.98, $SE = .03$, $Z = 24.42$, $p < .001$, and was higher for the alphabetic condition, $\hat{\beta} = -0.63$, OR = .53, $SE = .22$, $Z = -2.89$, $p = .004$. However, these main effects were qualified by an interaction between Writing System and Day, $\hat{\beta} = .11$, OR = 1.11, $SE = .06$, $Z = 1.99$, $p = .047$. This interaction reflects that while there was an early advantage for the alphabetic system, performance for the two writing systems converged by the end of training.

Figure 3.7B shows average RT for alphabetic and logographic conditions on the same training days. There were main effects of Day and Writing System, as RT decreased during training, ˆβ = -.10, *SE* = .00, *t* = -41.44, *p* < .001, and was faster for the logographic condition, ˆβ = -.34, *SE* = .04, *t* = -9.62, *p* < .001. There was no interaction between Writing System and Day, ˆβ = -.00, *SE* = .00, *t* = -.49, *p* = .623.

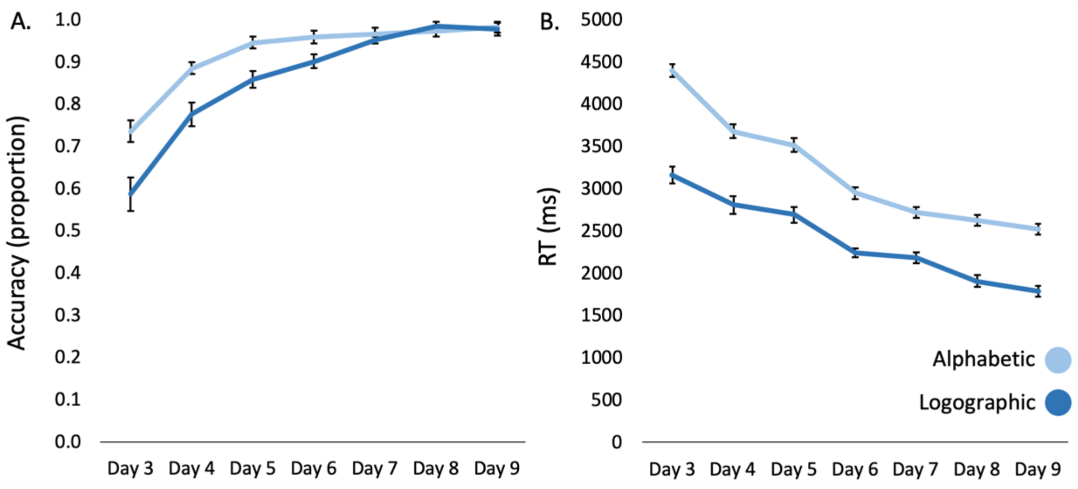


Figure 3.7. Accuracy and Average RT on Saying the Meaning During Training

Note. Accuracy (A) and average RT (B) on Saying the Meaning for alphabetic and logographic conditions over seven training days. Averages were calculated from the final 24 trials sampled from each Writing System and Day. Error bars denote within-subjects SE.

Semantic orthographic search

24 participants performed 24 trials per Writing System on Days 3-9, totalling 8,064 data points. Figure 3.8A shows average accuracy for alphabetic and logographic conditions on each day the task was performed. There were main effects of Day and Writing System, as accuracy increased during training, ˆβ = .63, OR = 1.89, *SE* = .02, *Z* = 26.61, *p* < .001, and was higher for the alphabetic condition, ˆβ = -1.03, OR = .36, *SE* = .22, *Z* = -4.61, *p* < .001. These main effects were qualified by an

interaction between Writing System and Day, ˆβ = .32, OR = 1.37, *SE* = .05, *Z* = 6.90, *p* < .001. This interaction demonstrates that while performance was initially higher for the alphabetic writing system, it converged for both writing systems by the end of training. Figure 3.8B shows average RT for alphabetic and logographic conditions on the same training days. There were main effects of Day and Writing System, as RT decreased during training, ˆβ = -.10, *SE* = .00, *t* = -24.62, *p* < .001, and was faster for the logographic condition, ˆβ = -.26, *SE* = .02, *t* = -16.32, *p* < .001. Finally, there was an interaction between Writing System and Day, ˆβ = -.02, *SE* = .01, *t* = -2.22, *p* = .027. This interaction reflects a more rapid improvement in response time for the alphabetic writing system than for the logographic system.

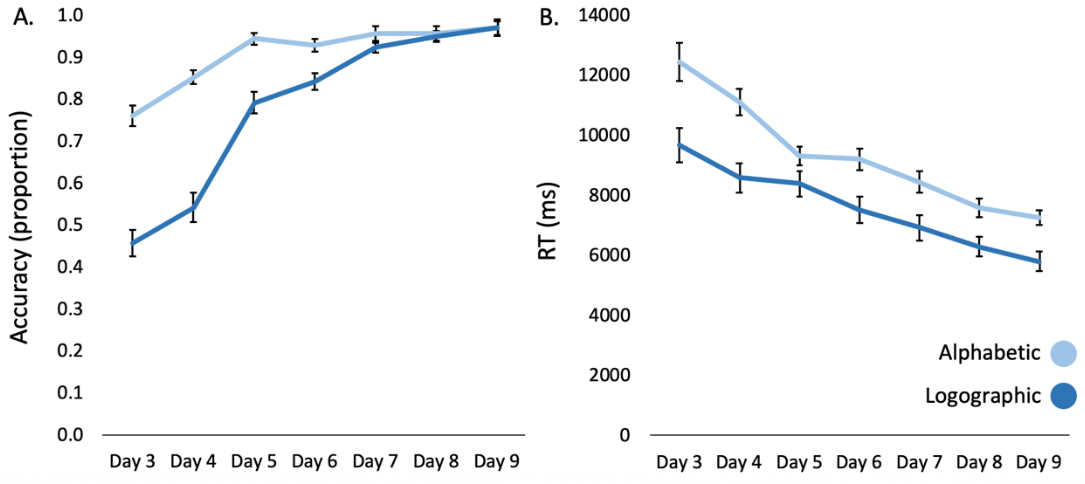


Figure 3.8. Accuracy and Average RT on Semantic Orthographic Search During Training

Note. Accuracy (A) and average RT (B) on Semantic Orthographic Search for alphabetic and logographic conditions over seven training days. Error bars denote within-subjects SE.

To summarise, participants learned both writing systems to a high degree of accuracy (above 90% for all tasks by the end of training) and showed continual increase in speed. No main effects of Writing System were observed on P-S training tasks (Picture Naming and Picture Search). However, consistent interactions between

Writing System and Day indicated that accuracy improved more quickly for the alphabetic writing system, while performance converged by the end of training for both systems. For both Picture Naming and Picture Search tasks, participants achieved 60% accuracy and similar RT for both writing systems on the first day. During training, they gradually approached ceiling and reduced RT to approximately 1,250ms when responding verbally. Further, there was a consistent benefit for O-P training tasks (Reading Aloud and Auditory Orthographic Search) for the alphabetic system. Participants learned most pronunciations on the first training day and struggled to associate sounds and spellings from the logographic system. On O-P tasks, verbal RTs were faster for the alphabetic system, but participants selected written pseudowords from all items more efficiently for the logographic system. Finally, on O-S tasks (Saying the Meaning and Semantic Orthographic Search) a benefit existed for the logographic system in terms of speed and, while accuracy was initially higher for the alphabetic system, the two writing systems quickly converged.

3.3. Performance During Testing

LME models were constructed to assess performance on behavioural tests and Semantic Monitoring as a function of Writing System. Behavioural tests were performed on Day 10; Semantic Monitoring was performed on Days 11 and 13 while participants were lying down in an MRI scanner (see Figure 2.4 in chapter 2 for an overview of the procedure). Accuracy was modelled using a Binomial (logistic) distribution. In contrast, RT was modelled using a Poisson (linear) distribution and a log transformation was performed for all tasks except Semantic Monitoring as RT data were normally distributed. All datapoints were included in accuracy analyses, while RT analyses only included correct responses and excluded distractor trials for

Lexical Decision and trials where participants should not have responded (No-Go trials) for Semantic Monitoring. Furthermore, we plotted histograms to review the distribution of RT data and remove outliers (as per Rastle, Davis, Marslen-Wilson, & Tyler, 2000). As the distribution of RT data varied across tasks, the RTs of outliers also varied across tasks. Outlier removal always occurred prior to the calculation of condition means. LME models included random intercepts for 24 Subjects and 48 Semantic Objects. However, semantic object was removed as a random factor for accuracy analysis of Phoneme Reversal and for accuracy and RT analyses of Lexical Decision as these models failed to converge. Spoken and written pseudowords were not included as random factors as they were fully counterbalanced. Finally, to help us interpret the results of our LME models, contrasts were specified for Writing System to ensure that resulting values for intercept and fixed effects corresponded to the grand mean and main effects, respectively. Model equations were as follows:

Accuracy: glmer(Acc ~ WritingSystem + (1|Subject) + (1|Sem), data=results, family=binomial)

RT: lmer(logRT ~ WritingSystem + (1|Subject) + (1|Sem), data=correct).

In addition to using LME models to compare the impact of Writing System on accuracy for Lexical Decision and Semantic Monitoring, paired samples t-tests compared discriminability between different stimuli to mitigate against biased responding. d’ measured the ability to discriminate between trained words and untrained non-words for Lexical Decision and whether to respond during Semantic Monitoring. Hit rate (H) (e.g., proportion of ‘yes’ responses to trained pseudowords) and false alarm rate (FA) (e.g., proportion of 'yes' responses to untrained distractors) was used to calculate the sensitivity measure of discriminability, *d'* = *z*(H) – *z*(FA).

Picture naming

24 participants performed 24 trials per Writing System, totalling 1,152 data points. 12 outliers exceeding 4,000 ms were removed from nine participants' data. Seven were associated with the alphabetic condition; five were from the logographic condition. Figure 3.9 shows accuracy (A) and RT (B) for alphabetic and logographic conditions. Participants learned the items to a high degree of accuracy, with no difference in performance between Writing Systems; Accuracy, $\hat{\beta} = .01$, OR = 1.01, $SE = .52$, $Z = .03$, $p = .980$, RT, $\hat{\beta} = -.03$, $SE = .04$, $t = -.91$, $p = .366$.

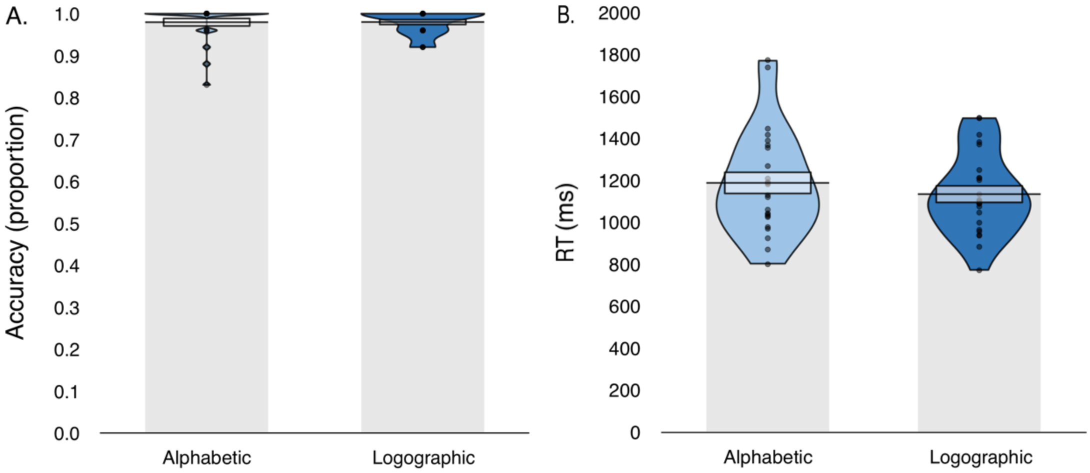


Figure 3.9. Accuracy and Average RT on Picture Naming During Testing

Note. Accuracy (A) and average RT (B) on Picture Naming for alphabetic and logographic conditions during testing. Centre lines show the means, surrounding bars denote within-subject SE, dots represent individual participants, and blue shapes reflect the distribution across participants.

Reading aloud

24 participants performed 72 trials per Writing System, totalling 3,456 data points. Eight outliers exceeding 6,750 ms were removed from six participants' data. These outliers were all from the logographic condition. Figure 3.10 shows accuracy (A) and RT (B) for alphabetic and logographic conditions. Participants learned the items from both Writing Systems to a high degree of accuracy, while accuracy was higher and RTs were faster for the alphabetic condition; Accuracy, $\hat{\beta} = -1.27$, OR = .28, *SE* = .26, $Z = -4.82$, $p < .001$, RT, $\hat{\beta} = .22$, *SE* = .03, $t = 7.51$, $p < .001$.

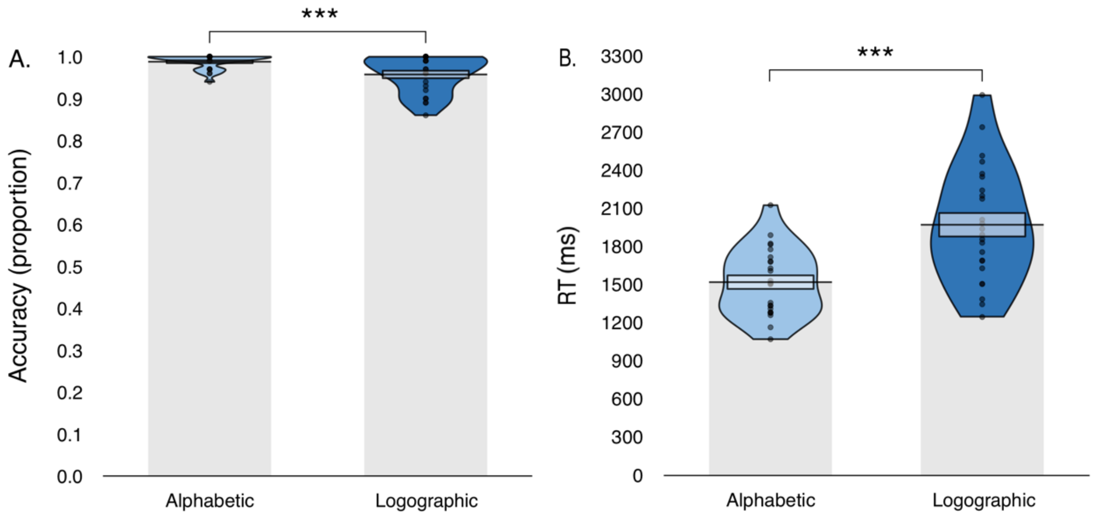


Figure 3.10. Accuracy and Average RT on Reading Aloud During Testing

Note. Accuracy (A) and average RT (B) on Reading Aloud for alphabetic and logographic conditions during testing. Centre lines show the means, surrounding bars denote within-subject SE, dots represent individual participants, and blue shapes reflect the distribution across participants.

Saying the meaning

24 participants performed 24 trials per Writing System, totalling 1,152 data points. Two outliers exceeding 7,600 ms were removed from two participants' data. One

was from the alphabetic condition; one was from the logographic condition. Figure 3.11 shows accuracy (A) and RT (B) for alphabetic and logographic conditions. Participants successfully learned the items, with no difference in accuracy between Writing Systems and faster RTs for the logographic condition; Accuracy, $\hat{\beta} = -.30$, OR = .75, $SE = .48$, $Z = -.62$, $p = .538$, RT, $\hat{\beta} = -.26$, $SE = .04$, $t = -6.74$, $p < .001$.

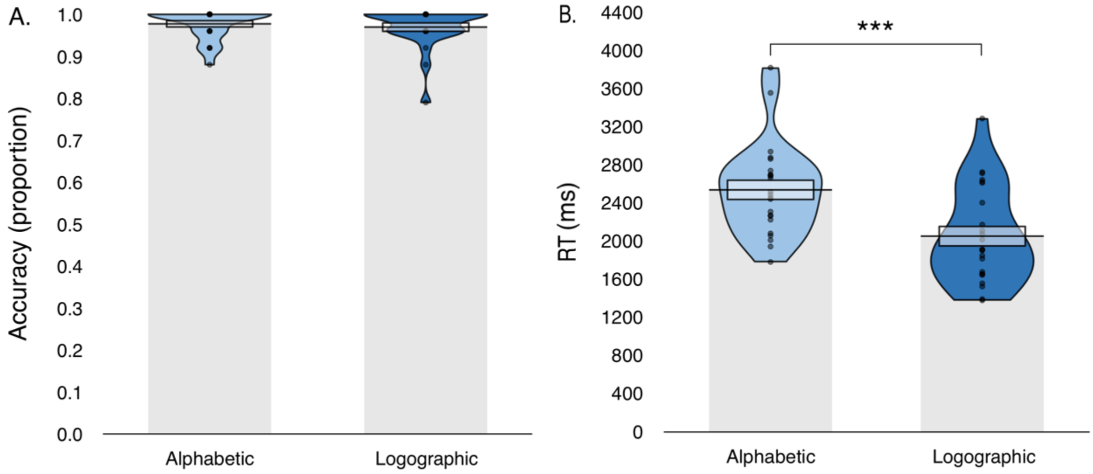


Figure 3.11. Accuracy and Average RT on Saying the Meaning During Testing

Note. Accuracy (A) and average RT (B) on Saying the Meaning for alphabetic and logographic conditions during testing. Centre lines show the means, surrounding bars denote within-subject SE, dots represent individual participants, and blue shapes reflect the distribution across participants.

Auditory shadowing

24 participants performed 24 trials per Writing System, totalling 1,152 data points. Two outliers from the alphabetic condition exceeding 1,950 ms were removed. All participants achieved 100% accuracy for the alphabetic and logographic conditions. Figure 3.12 shows average RT for both conditions; no difference in performance was observed between Writing Systems, $\hat{\beta} = -.00$, $SE = .01$, $t = .04$, $p = .968$.

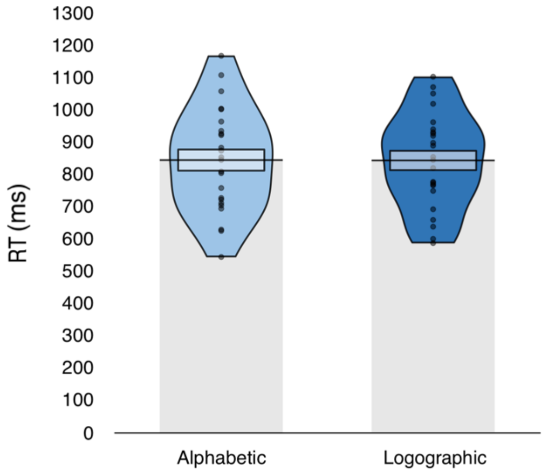


Figure 3.12. Average RT on Auditory Shadowing During Testing

Note. Average RT on Auditory Shadowing for alphabetic and logographic conditions during testing. Centre lines show the means, surrounding bars denote within-subject SE, dots represent individual participants, and blue shapes reflect the distribution across participants.

Phoneme reversal

24 participants performed 24 trials per Writing System, totalling 1,152 data points. One outlier from the logographic condition exceeding 7,100 ms was removed. Figure 3.13 shows accuracy (A) and RT (B) for alphabetic and logographic conditions. While accuracy was high for both Writing Systems, participants responded more accurately to the alphabetic condition with no difference in RT; Accuracy, $\hat{\beta} = -.95$, OR = .39, $SE = .40$, $Z = -2.37$, $p = .018$, RT, $\hat{\beta} = .01$, $SE = .04$, $t = .38$, $p = .707$.

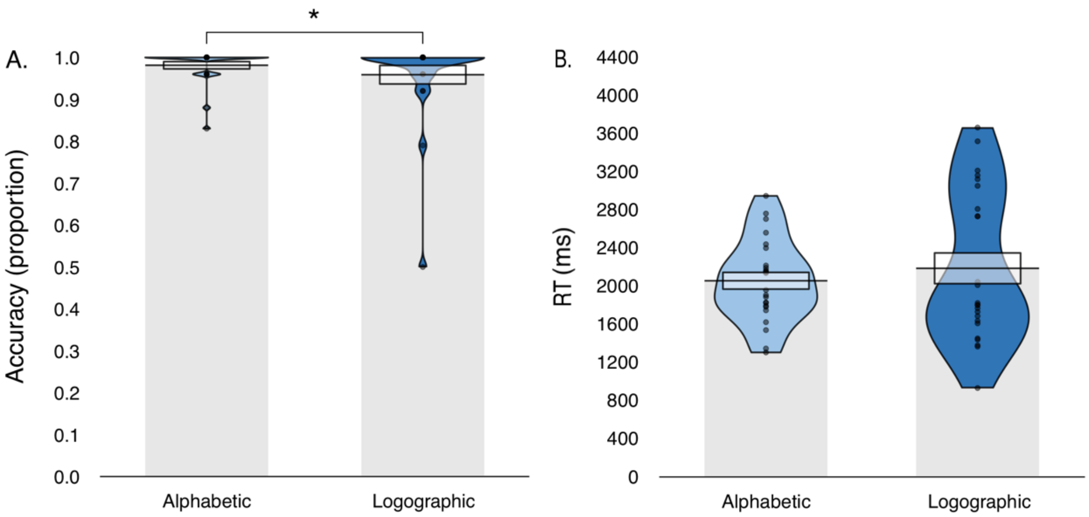


Figure 3.13. Accuracy and Average RT on Phoneme Reversal During Testing

Note. Accuracy (A) and average RT (B) on Phoneme Reversal for alphabetic and logographic conditions during testing. Centre lines show the means, surrounding bars denote within-subject SE, dots represent individual participants, and blue shapes reflect the distribution across participants.

Auditory lexical decision

24 participants performed 96 trials per Writing System, totalling 4,608 data points, which presented both trained and untrained spoken pseudowords. Accuracy analysis included all datapoints while RT analysis excluded 2,304 distractor trials. Six outliers exceeding 4,150 ms were removed from four participants' data. Two were associated with the alphabetic condition; four were from the logographic condition.

Figure 3.14A shows accuracy for alphabetic and logographic conditions. Participants were consistently accurate, with no evidence of any difference in the proportion of trained and untrained items identified for each Writing System, $\hat{\beta} = -.14$, OR = .87, $SE = .37$, $Z = -.37$, $p = .713$. Table 3.1 shows accuracy for each outcome used to calculate d' for alphabetic and logographic conditions. Participants successfully discriminated between trained and untrained items, with no difference in discriminability observed between Writing Systems, *t*(23) = .17, *p* = .867. Finally, Figure 3.14B shows RT for trained pseudowords and untrained pseudowords from alphabetic and logographic conditions. No difference in RT for trained words was observed between Writing Systems, $\hat{\beta}$ = .02, *SE* = .01, *t* = 1.39, *p* = .165.

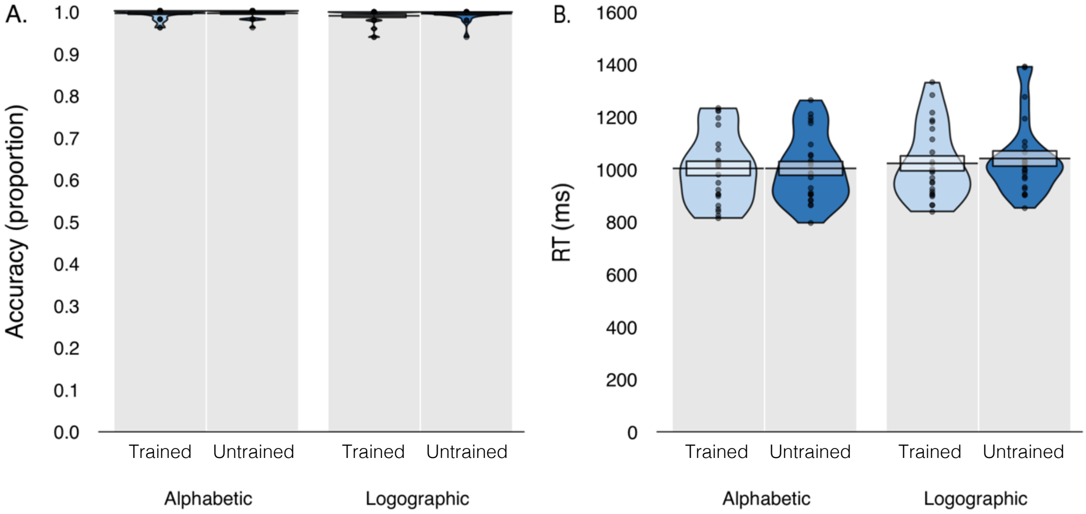


Figure 3.14. Accuracy and Average RT on Auditory Lexical Decision During Testing

Note. Accuracy (A) and average RT (B) on Auditory Lexical Decision for trained pseudowords and untrained pseudowords associated with alphabetic and logographic conditions during testing. Centre lines show the means, surrounding bars denote within-subject SE, dots represent individual participants, and blue shapes reflect the distribution across participants.

Table 3.1. *Accuracy and d' on Auditory Lexical Decision During Testing*

Writing System	Hit	Correct Rejection	Miss	False Alarm	d'
Alphabetic	0.99	0.99	0.01	0.01	4.46
Logographic	0.99	1.00	0.01	0.00	4.44

Note. Accuracy on Auditory Lexical Decision for each potential outcome (Hit, Correct Rejection, Miss, False Alarm) used to calculate d' scores for alphabetic and logographic writing systems.

Visual lexical decision

24 participants performed 96 trials per Writing System, totalling 4,608 data points, which presented both trained and untrained written pseudowords. Accuracy analysis included all datapoints while RT analysis excluded 2,304 distractor trials. Five outliers exceeding 12,850 ms were removed from five participants' data. Three were associated with the alphabetic condition; two were from the logographic condition.

Figure 3.15 shows accuracy (A) and RT (B) for alphabetic and logographic conditions. Participants were highly accurate, while the proportion of trained and untrained items identified was significantly higher for the alphabetic condition, $\hat{\beta} = -.77$, OR = .47, $SE = .14$, $Z = -5.56$, $p < .001$. This finding was consistent with d' analysis (see Table 3.2) which showed an increased ability to discriminate between trained and untrained items associated with the alphabetic system, $t(23) = 3.48$, $p = .002$. However, interpretation of enhanced accuracy for the alphabetic condition is complicated by evidence for a speed-for-accuracy trade-off, with faster responding observed for trained logographic items, $\hat{\beta} = -.47$, $SE = .02$, $t = -23.70$, $p < .001$.

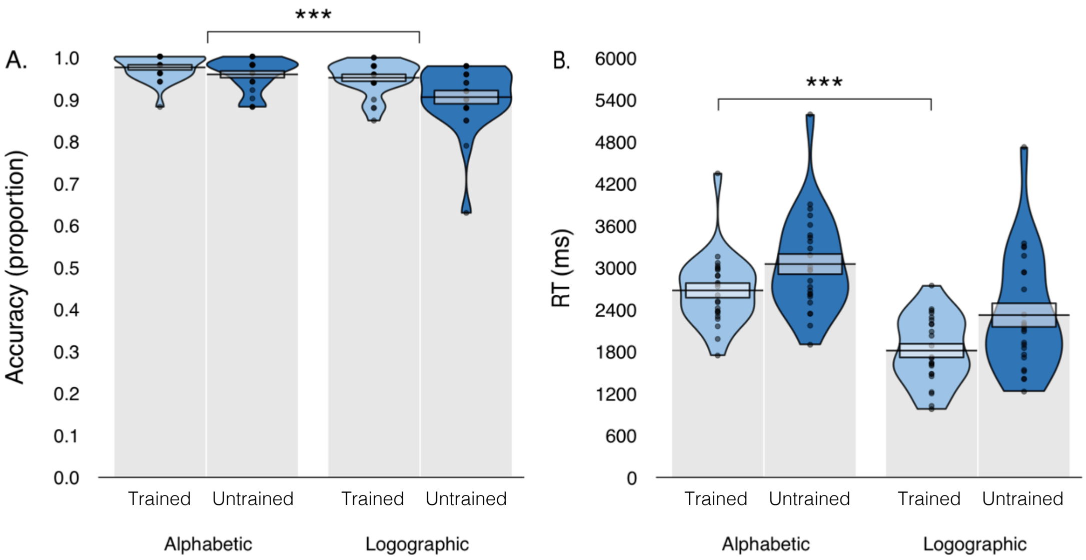


Figure 3.15. Accuracy and Average RT on Visual Lexical Decision During Testing

Note. Accuracy (A) and average RT (B) on Visual Lexical Decision for trained pseudowords and untrained pseudowords associated with alphabetic and logographic conditions during testing. Centre lines show the means, surrounding bars denote within-subject SE, dots represent individual participants, and blue shapes reflect the distribution across participants.

Table 3.2. *Accuracy and d' on Visual Lexical Decision During Testing*

Writing System	Hit	Correct Rejection	Miss	False Alarm	d'
Alphabetic	0.97	0.96	0.03	0.04	3.79
Logographic	0.95	0.90	0.05	0.10	3.17

Note. Accuracy on Visual Lexical Decision for each potential outcome (Hit, Correct Rejection, Miss, False Alarm) used to calculate d' scores for alphabetic and logographic writing systems.

Auditory semantic monitoring

24 participants performed 192 trials per Writing System across two runs, totalling 9,216 data points, which included Go and No-Go trials. Accuracy analysis included all datapoints while RT analysis excluded all trials where participants should not

have responded (No-Go trials). Sixty-two outliers below 700 ms were removed from 21 participants' data, likely caused by late responses to the previous trial. Forty were associated with the alphabetic condition; 22 were from the logographic condition.

Figure 3.16A shows accuracy for alphabetic and logographic conditions. Participants were highly accurate, with no evidence of any difference in the proportion of Go and No-Go trials identified for each Writing System, $\hat{\beta} = -.05$, OR = .96, $SE = .20$, $Z = -.22$, $p = .824$. This result is consistent with d' analysis (see Table 3.3) with no difference in discriminability between Go and No-Go trials observed between Writing Systems, $t(23) = 1.24$, $p = .229$. Finally, Figure 3.16B shows average RT for Go trials associated with alphabetic and logographic conditions; no difference was observed between Writing System, $\hat{\beta} = -23.75$, $SE = 36.19$, $t = -.66$, $p = .515$.

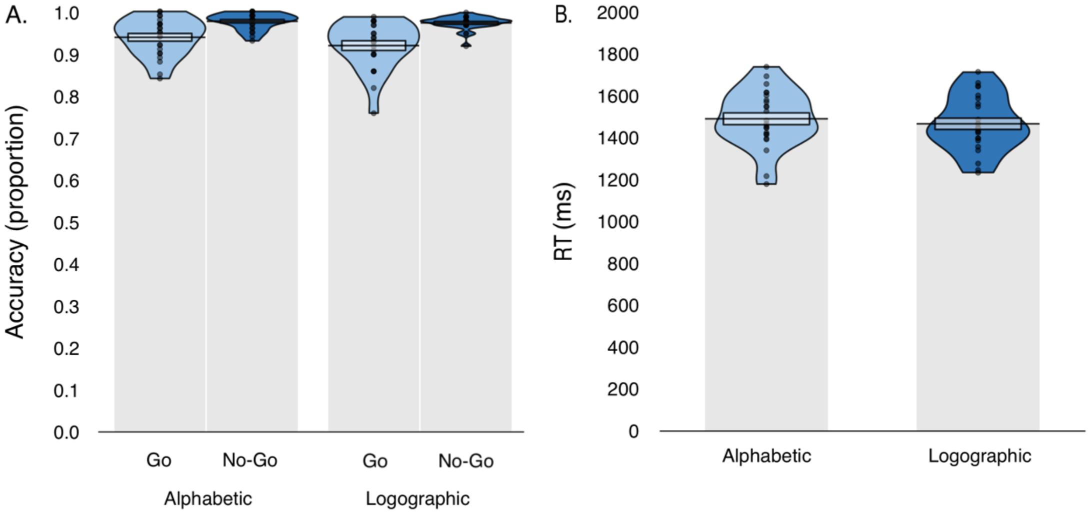


Figure 3.16. Accuracy and Average RT on Auditory Semantic Monitoring During Scanning

Note. Accuracy (A) for Go and No-Go trials and average RT (B) for Go trials associated with alphabetic and logographic conditions on Auditory Semantic Monitoring during testing. Centre lines show the means, surrounding bars denote within-subject SE, dots represent individual participants, and blue shapes reflect the distribution across participants.

Table 3.3. *Accuracy and d' on Auditory Semantic Monitoring During Scanning*

Writing System	Hit	Correct Rejection	Miss	False Alarm	d'
Alphabetic	0.94	0.98	0.06	0.02	3.78
Logographic	0.92	0.98	0.08	0.02	3.56

Note. Accuracy on Auditory Semantic Monitoring for each potential outcome (Hit, Correct Rejection, Miss, False Alarm) used to calculate d' scores for alphabetic and logographic writing systems.

Visual semantic monitoring

24 participants performed 192 trials per Writing System across two runs, totalling 9,216 data points, which included both Go and No-Go trials. Accuracy analysis included all datapoints while RT analysis excluded No-Go trials. Twenty-seven outliers below 500 ms were removed from 11 participant's data. Sixteen were associated with the alphabetic condition; 11 were from the logographic condition.

Figure 3.17A shows accuracy for alphabetic and logographic conditions. Participants were reasonably accurate for both Writing Systems, while the proportion of Go and No-Go trials identified was significantly higher for the logographic condition, $\hat{\beta}$ = .52, OR = 1.68, $SE = .12$, $Z = 4.21$, $p < .001$. This result is consistent with d' analysis (see Table 3.4) which showed an increased ability to discriminate between Go and No-Go trials for the logographic system, $t(23) = -4.36$, $p < .001$. Finally, Figure 3.17B shows RT for Go trials associated with both conditions. Participants achieved fast RTs for both Writing Systems, while faster RTs for Go trials were observed for the logographic condition, $\hat{\beta} = -420.89$, $SE = 30.64$, $t = -13.74$, $p < .001$.

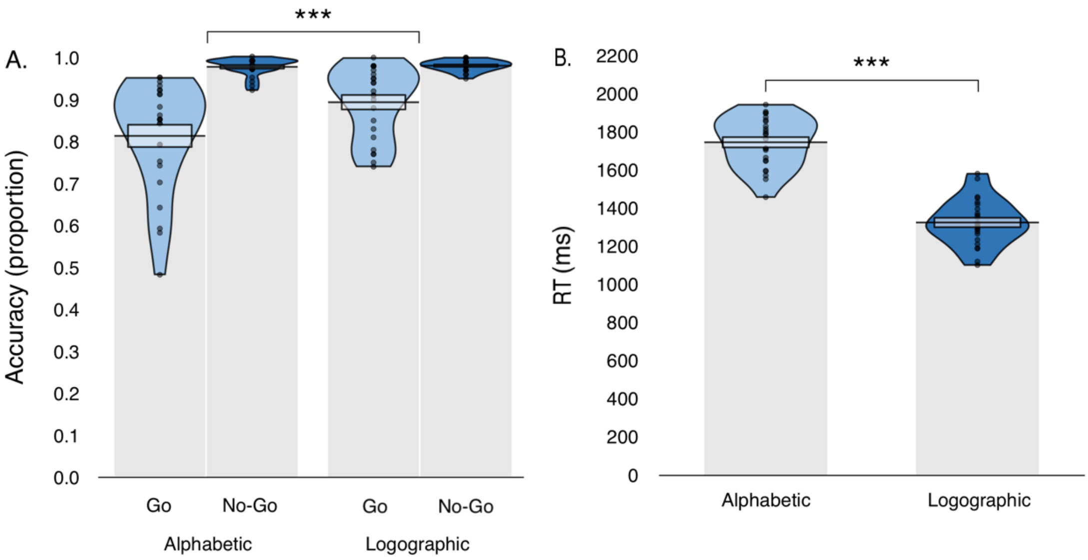


Figure 3.17. Accuracy and Average RT on Visual Semantic Monitoring During Scanning

Note. Accuracy (A) for Go and No-Go trials and average RT (B) for Go trials associated with alphabetic and logographic conditions on Visual Semantic Monitoring during testing. Centre lines show the means, surrounding bars denote within-subject SE, dots represent individual participants, and blue shapes reflect the distribution across participants.

Table 3.4. *Accuracy and d' on Visual Semantic Monitoring During Scanning*

Writing System	Hit	Correct Rejection	Miss	False Alarm	d'
Alphabetic	0.81	0.98	0.19	0.02	3.06
Logographic	0.89	0.98	0.11	0.02	3.57

Note. Accuracy on Visual Semantic Monitoring for each potential outcome (Hit, Correct Rejection, Miss, False Alarm) used to calculate d' scores for alphabetic and logographic writing systems.

Two data collection errors occurred while participants performed Auditory and Visual Semantic Monitoring in the MRI scanner. On Day 11, button-presses were not recorded for two participants who consequently repeated the procedure during a third scan three days after their second fMRI scan (Day 13) as behavioural performance could not be assessed. In addition, the number of trials participants should have responded to (Go trials) varied across participants. Each run of Semantic Monitoring included 12 blocks of 16 trials. Each block presented a target semantic category and should have included four pseudowords associated with meanings from each category (animals, fruit or vegetables, tools, and vehicles). As participants were tasked to respond only when the meaning of pseudowords matched the current target category, each block should have contained four Go trials. However, the number of pseudowords associated with each semantic category, and consequently the number of Go trials, varied within each block for 12 participants. Nevertheless, all pseudowords were presented to all participants eight times across the 12 blocks.

To assess whether performance was impacted by the number of Go trials participants received, we compared d' for those who should have responded four times per block (Group 1) and those who received a different number of Go trials (Group 2). Table 3.5 shows d’ scores for each Group and Writing System. A two-way independent samples ANOVA was conducted to compare performance on Auditory Semantic Monitoring as a function of Group and Writing System. There was no main effect of Group, $F(1,22) = 2.075$, $p = .164$, or Writing System, $F(1,22) = 2.677$, $p = .116$, nor an interaction between Group and Writing System, $F(1,22) = .255$, $p = .618$. In addition, we correlated d' with the total number of Go trials that participants from Group 2 received. Group 1 was excluded from this correlation analysis as they were not impacted by the error. No relationship was observed between d' and the total number of Go trials for alphabetic, $r = -.055$, $p = .865$, or logographic, $r = -.262$, $p = .411$, conditions. Combined, these results suggest that the number of Go trials received during Auditory Semantic Monitoring did not impact on performance.

Table 3.5. *d' on Auditory Semantic Monitoring During Scanning*

Writing System	Group 1	Group 2
Alphabetic	3.80	3.61
Logographic	3.67	3.37

Note. d' for participants who should have responded four times per block (Group 1) and those who received a different number of Go trials (Group 2) during Auditory Semantic Monitoring

A two-way independent samples ANOVA was conducted to compare d' on Visual Semantic Monitoring as a function of Group and Writing System. Table 3.6 shows d' scores for each Group and Writing System. There was no main effect of Group, $F(1,22) = 1.697$, $p = .206$, or Writing System, $F(1,22) = 0.734$, $p = .401$, nor an interaction between Group and Writing System, $F(1,22) = 0.156$, $p = .697$. In addition, we correlated d' with the total number of Go trials that participants from Group 2 received. No relationship was observed between d' and the total number of Go trials received for alphabetic, $r = .04$, $p = .901$, or logographic, $r = .069$, $p = .831$, conditions. Combined, these results suggest that the number of Go trials participants received during Visual Semantic Monitoring did not impact on performance.

To summarise, participants learned items from both writing systems to a high degree of accuracy (consistently above 90%) and responded within 2500ms when a time-limit was enforced. There was no impact of Writing System on P-S tasks (Picture Naming and Auditory Semantic Monitoring) and little evidence for an orthographic effect on spoken language processing; participants were highly accurate and responded quickly on Auditory Shadowing and Auditory Lexical Decision for both writing systems. Nevertheless, Writing System exerted a subtle impact on phonemic awareness as accuracy was higher for the alphabetic condition on Phoneme Reversal,

Table 3.6. *d' on Visual Semantic Monitoring During Scanning*

Writing System	Group 1	Group 2
Alphabetic	3.38	3.10
Logographic	3.55	3.17

Note. d' for participants who should have responded four times per block (Group 1) and those who received a different number of Go trials (Group 2) during Visual Semantic Monitoring

although this effect was driven by two participants who performed poorly on the logographic condition. Further, performance on Reading Aloud (an O-P task) was superior in the alphabetic system and participants could more accurately identify trained pseudowords from the alphabetic condition during Visual Lexical Decision. However, interpretation of Visual Lexical Decision is complicated by a speed-for-accuracy trade-off, as RTs were faster for the logographic condition. Finally, performance on O-S tasks (Saying the Meaning and Visual Semantic Monitoring) was superior in the logographic condition as participants identified the meaning of written pseudowords more quickly and accurately than in the alphabetic condition.

3.4. Conclusions

We hypothesised that the orthographic transparency of a writing system will determine the "division of labour" between phonological (O-P) and semantic (O-S) processes during reading aloud and comprehension (Plaut et al., 1996; Smith et al., 2021). As transparent alphabetic writing systems feature consistent, one-to-one mappings between symbols and sounds, we predicted that sub-word spelling-sound information will be favoured, strengthening O-P mappings. As opaque logographic writing systems lack O-P systematicity (instead featuring arbitrary, whole-word mappings between spelling and sounds), we predicted that O-S will be favoured as the more efficient mapping (Seidenberg, 2011). Overall, these findings indicate striking differences in the division of labour between phonological and semantic processes. Performance on Reading Aloud (an O-P task) was superior in the alphabetic writing system and participants could more accurately identify trained pseudowords from the alphabetic condition during Visual Lexical Decision. Performance on O-S tasks (Saying the Meaning and Visual Semantic Monitoring) was superior in the logographic condition as participants identified the meaning of written pseudowords more quickly and accurately than in the alphabetic condition. Thus, the alphabetic system appears to favour systematic O-P mappings during reading acquisition. Participants may have read alphabetic words aloud by accessing phonology directly from orthography while comprehending meaning by accessing semantics from orthography via phonology. Equally, the logographic system appears to favour arbitrary, whole-word O-S mappings during reading acquisition. Although sounds and meanings of written words can be jointly determined by both pathways, these findings indicate that the nature of the writing system impacts on the development of direct (O-P) and phonologically mediated (O-P-S) pathways during learning, and consequently reading aloud and comprehension (Taylor et al., 2017).

In addition, we hypothesised that the orthographic transparency of a writing system will determine how learning to read impacts on spoken language processing (P-S). As transparent alphabetic writing systems feature consistent, one-to-one mappings between symbols and sounds, we predicted that spoken language processing will be uniquely impacted by reading acquisition (Smith et al., 2021). However, these findings indicate no effect of orthographic transparency on spoken language processing. There was no impact of Writing System on P-S tasks (Picture Naming and Auditory Semantic Monitoring) and no clear evidence for an orthographic effect on spoken language processing; participants were highly accurate and responded quickly on Auditory Shadowing, Auditory Lexical Decision, and Phoneme Reversal for both writing systems. Overall, these findings support our hypothesis that the orthographic transparency of a writing system will determine the division of labour between phonological (O-P) and semantic (O-S) processes but do not support our hypothesis that learning to read will impact on spoken language processing.

CHAPTER IV: NEUROIMAGING METHODS

4.1. Data Acquisition

Semantic monitoring

Participants were tasked to monitor the meanings of trained spoken (*Auditory Semantic Monitoring*) and written (*Visual Semantic Monitoring*) items while neural responses were recorded using fMRI. Spoken pseudowords were presented over high quality etymotic earphones (Sensimetrics); written pseudowords were projected onto a screen behind the scanner bore and viewed using a mirror positioned on the head coil. All participants completed two alternating runs of Auditory and Visual Semantic Monitoring. Twelve participants began with Auditory Semantic Monitoring; 12 began with Visual Semantic Monitoring. In each run, all items from both writing systems were presented four times in a randomised order during 12 blocks of 16 trials. Each block presented stimuli from one writing system and alphabetic and logographic systems alternated between blocks. Twelve participants began with a block presenting alphabetic stimuli; 12 began with logographic stimuli. A target semantic category (animals, fruit or vegetables, tools, or vehicles) was displayed at the beginning of each block and all categories were presented three times in a randomised order.

On each trial, participants responded using their right index finger and an MRI-compatible button box (NATA Technologies) if the meaning of the presented item matched the target semantic category. All responses and reaction times (RT) were recorded using E-Prime (Version 2.0; Psychology Software Tools, 2003). A blank screen was presented for 12 seconds after each block and participants received simple feedback at the end of every third block; “Well Done! It looks like you're concentrating on the task" if they responded during any trial or "Oops! Try and concentrate! You didn't respond to any of the trials". Figure 2.3 (row E) and 'fMRI scanning' in chapter 2 provide more details about the semantic monitoring tasks.

Scanning Parameters

Structural and functional MRI data were obtained using a 3T Siemens Trio scanner (Seimens Medical Systems, Erlangen, Germany) and a 32-channel head coil. For each participant, high resolution T_1-weighted structural images were recorded using a Magnetisation Prepared Rapid Acquisition Gradient Echo sequence (MPRAGE; 1 mm slice thickness, 1 mm isotropic resolution, repetition time (TR) = 1830 ms, echo time (TE) = 3.03 ms, inversion time (TI) = 1100 ms, flip angle (FA) = 11°, field of view (FOV) = 256 x 160 x 256 mm). Functional images were acquired with a T_2*-weighted gradient echoplanar imaging (EPI) sequence with blood oxygenation level-dependent contrast and fat saturation. Further, we obtained 32 interleaved axial slices in descending order using the following acquisition parameters: 3 mm slice thickness, .75 mm (25%) interslice gap, 3 mm isotropic spatial resolution, TE = 30 ms, FA = 78°, FOV = 192 mm, 64 x 64 data matrix. The acquisition volume was angled to cover the whole brain, avoiding the eyes and including the cerebellum, but failed to cover the top of the parietal lobe for some participants. Six dummy scans were included at the beginning of each run to ensure that steady-state magnetisation was reached. All dummy scans were excluded from subsequent analyses.

For Auditory Semantic Monitoring, we used a sparse imaging sequence (TR = 3,000 ms, TA = 2,000 ms) and presented one spoken pseudoword between volume acquisitions (Edmister, Talavage, Ledden, & Weisskoff, 1999). Spoken pseudowords were presented with a fixation cross which remained for the duration of each trial (see Figure 4.1, row A for a summary of the scanning protocol for Auditory Semantic Monitoring). Acquisition was synchronised with E-Prime using transistor-transistor logic pulse inputs from the MRI scanner to ensure each acquisition began 1,000 ms after trial onset. Overall, 258 EPI images were acquired during each 12.9-minute run. For Visual Semantic Monitoring, we used a continuous imaging design (TR = 2,000 ms, TA = 2,000 ms) and presented written pseudowords for 2,500 ms followed by a 500ms fixation cross per trial (see Figure 4.1, row B for a summary of the scanning protocol). Overall, 382 EPI images were acquired during each 12.7-minute run.

4.2. Pre-processing

Raw data were converted into Brain Imaging Data Structure format (BIDS; Gorgolewski et al., 2016). Functional and structural image pre-processing and analysis was achieved using MATLAB (MathWorks) and an integrated pipeline using modules from the Automatic Analysis framework (AA version 5.0.0; Cusack et al., 2015) and functions from SPM12 (Wellcome Trust Centre for Functional Neuroimaging, London, www.fil.ion.ucl.ac.uk/spm). Structural images were aligned to Montreal Neurological Institute (MNI) space, corrected for intensity bias, and segmented into gray and white matter. We normalised processed structural images to MNI space using Diffeomorphic Anatomical Registration Through Exponentiated Lie Algebra (DARTEL; Ashburner, 2007). In addition, a study template combining structural images for all participants was created using non-linear registration via segmentation and was subsequently affine (linear) transformed to MNI space.

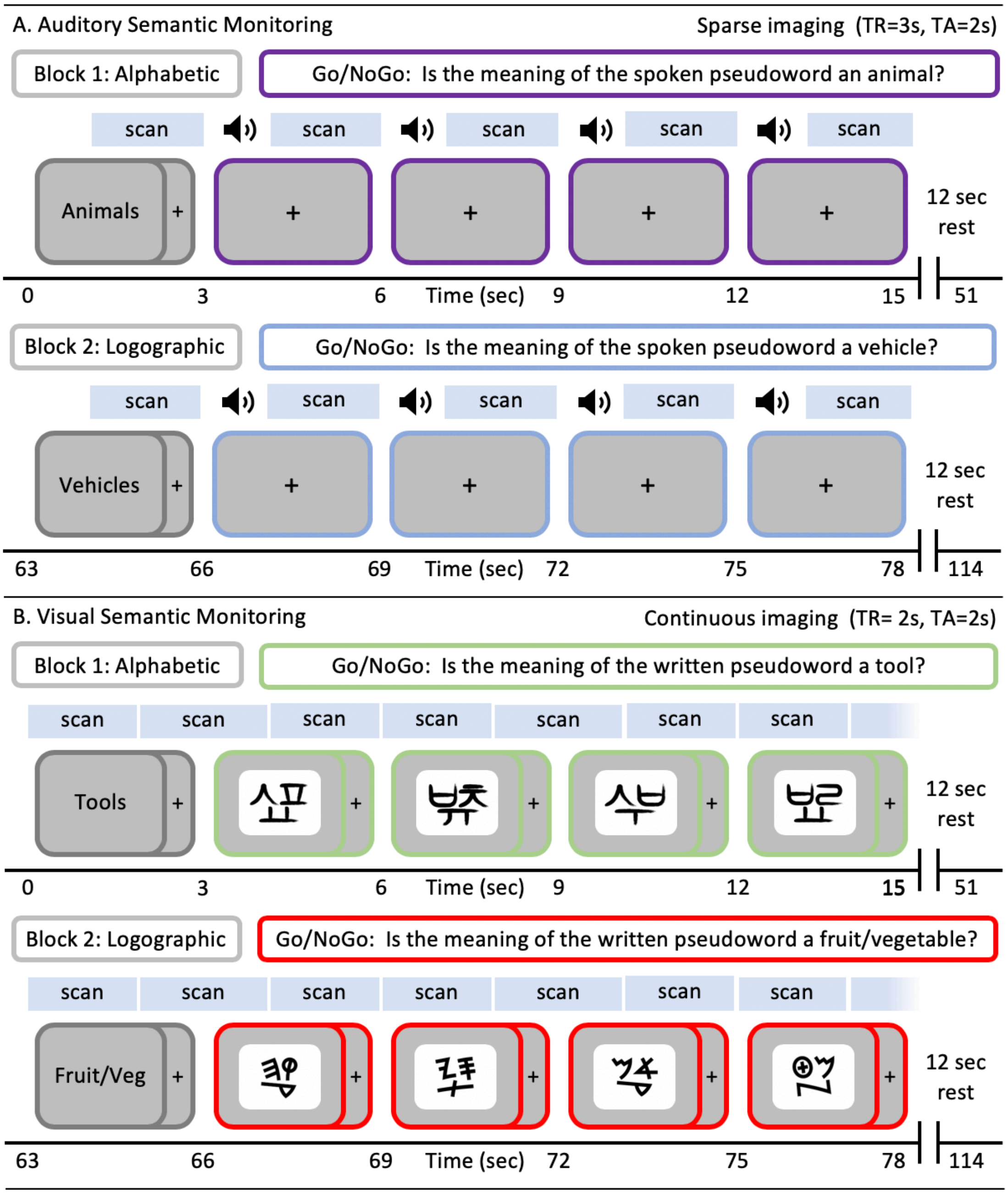


Figure 4.1. Summary of scanning protocols for Auditory (A) and Visual (B) Semantic Monitoring tasks. Note that this example represents six participants as we counterbalanced the order that stimuli from each writing system were presented, and which run was completed first (see OSF).

The first six volumes were removed from each run to avoid T1 saturation effects. EPI images were then spatially (rigid-body) and temporally realigned to the middle image in the series to correct for head movement and varying slice acquisition times (Friston et al., 1995). Realigned EPI images were co-registered to each participant's structural image (Ashburner & Friston, 1997) and normalised to MNI space using a rigid-body transformation and the warping parameters used to normalise their structural image. Normalised EPI images were then resampled to 3mm isotropic voxels and spatially smoothed using a 5mm full width at half maximum (FWHM) isotropic Gaussian Kernel. Finally, a gray matter mask was created for each participant by de-normalising and co-registering EPI images to gray matter tissue segmentation. Masks included voxels exceeding 10% probability of being gray matter (segmentation threshold = 0.1). A diagram presenting the entire AA pipeline can be found in the OSF storage for this project: https://osf.io/3q2jb/.

Quality assurance

Behavioural performance (accuracy and d'; see chapter 3 for more details) and head movement were reviewed for all participants and runs to assess engagement and the quality of recorded fMRI data. Time series difference analysis (Tsdiffana) plots were inspected before applying motion-correction to EPI images to determine whether peaks in the scaled variance of Bold Oxygen Level Dependent (BOLD) signal between volumes and slices were associated with motion. Following pre-processing, the degree of motion correction applied to each run was reviewed before identifying those still exceeding 2mm of movement. We then inspected raw EPI images associated with identified outliers and excluded five runs from analyses as movement was unresolved by motion correction: one Auditory Semantic Monitoring run from one participant, one Visual Semantic Monitoring run from a second participant, and one Auditory Semantic Monitoring run along with two Visual Semantic Monitoring runs from a third participant. In addition, volumes obtained after a pronounced head movement were removed from one run of Auditory Semantic Monitoring. Tsdiffana plots were then inspected to determine whether an acceptable amount of variance was caused by corrected head movement. Finally, one block was excluded from Visual Semantic Monitoring as the participant admitted to falling asleep. All blocks with no responses were reviewed for movement associated with sleep and none were excluded. No further runs were removed as performance was consistently high.

4.3. Univariate Analysis

General linear model

To estimate changes in neural activity in response to trained spoken and written pseudowords from different writing systems, we used a general linear model (GLM) approach. The analysis was implemented using fully pre-processed data (normalised, smoothed EPI images) from each participant. In any given voxel, the observed data, Y, was estimated as the relationship between model factors, X, each factor's contribution to the data, β, and noise, ε (i.e., $Y = X\beta + \varepsilon$). All events associated with one modality and each writing system were convolved with the canonical Haemodynamic Response Function (HRF) within SPM12 to create regressors in the model ($n = 2$; one per writing system). Neural responses to spoken pseudowords were modelled with a duration of 482.5 ms, the average duration of all trained auditory stimuli. Further, four outcomes associated with the semantic monitoring task (hit, miss, correct rejection, and false alarm) were modelled as a single event type and data from all four runs were combined for each modality. Motion correction parameters estimated during the spatial realignment stage of pre-processing were included as covariates. Sleep (i.e., whether participants were awake or asleep during a given block) was included as a regressor when modelling neural responses to written pseudowords to account for variance created by a single participant who fell asleep during one block of Visual Semantic Monitoring. Targets and rest blocks were included as regressors of no interest, while rest served as an implicit baseline for subsequent contrasts. Finally, high-pass temporal filtering (128 Hz) was applied to remove low-frequency signal drifts. All unreported parameters were set to defaults.

Univariate contrasts

Contrast images for each participant were created to compare different conditions by averaging trials across runs associated with each modality (i.e., visual and auditory). For each modality, voxel-wise contrasts aimed to identify brain regions exhibiting greater neural activation for all trained pseudowords than rest (all items > baseline), all trained pseudowords from the alphabetic writing system than rest (alphabetic > baseline), and all trained pseudowords from the logographic writing system than rest (logographic > baseline). Further, to identify brain regions exhibiting greater neural activation for items from different writing systems, we compared pseudowords from the alphabetic writing system to pseudowords from the logographic writing system (alphabetic > logographic) and vice versa (logographic > alphabetic).

Contrasts of parameter estimates were entered into group-level one-sample t-tests to compare first-level observations to the null hypothesis with participants as a random effect. In addition, voxel-wise conjunction analysis was performed on group-level t-maps to identify brain regions exhibiting significantly greater activation for both spoken and written pseudowords from the alphabetic writing system than rest (visual alphabetic > baseline x auditory alphabetic > baseline) and for both spoken and written pseudowords from the logographic system than rest (visual logographic > baseline x auditory logographic > baseline). For all group-level analyses, mean-centred accuracy scores on Spelling and Vocabulary tasks (see chapter 3) were added as covariates and any voxels located outside MNI space following normalisation were removed. Group-level results were thresholded at voxel-wise $p < .001$ (uncorrected), while only activations greater than a cluster-extent family wise error (FWE) threshold of $p < .05$ (corrected) were considered significant.

Region of Interest (ROI) analysis

To analysis was conducted to maximise sensitivity and specificity and ensure that differences between trained writing systems were fully understood. Taylor et al. (2013) found greater neural activation in posterior occipitotemporal cortex for pseudoword relative to word reading, and in left anterior fusiform for word relative to pseudoword reading. These same contrasts are relevant to the distinction between alphabetic and logographic writing systems. Pseudowords and alphabetic items may capitalise on one-to-one mappings between graphemes and phonemes, while known words and logographic items may be processed using whole-word mappings between spelling and meaning. We therefore investigated whether neural activity for written pseudowords shifted from alphabetic > logographic to logographic > alphabetic along the left posterior to anterior ventral occipitotemporal cortex (vOT).

8mm spherical ROIs were created using MarsBaR (Brett, Anton, Valabrègue, & Poline, 2002), a toolbox integrated into SPM12. First, six ROIs were constructed using peak neural activations from the group-level contrast all items > baseline for

Visual Semantic Monitoring. We selected peak activations from our own data that were closest to the six sets of coordinates defined by Vinckier et al. (2007). Five ROIs were shortlisted from those created using coordinates from our own data to avoid overlap between 8mm spheres while ensuring an even distribution along the ventral stream of the reading network. In addition, coordinates for left anterior fusiform were taken directly from Taylor et al. (2013) as no equivalent peak activation existed within the group-level contrast all items > baseline for Visual Semantic Monitoring. Consequently, the most anterior of the five existing ROIs was removed as it overlapped with the new ROI defined using coordinates from Taylor et al. (2013). Here, the latter was prioritised as it was more theoretically driven.

Figure 4.2 represents the location of the five ROIs used for univariate analysis. Table 4.1 provides additional information including their source, anatomical label, and coordinates. ROI analysis was achieved using the MarsBaR toolbox and was conducted on whole-brain first-level alphabetic > logographic t-maps created by contrasting neural responses to written pseudowords. Thus, ROI definition was independent of the contrast images used for analysis. T-values from voxels within each ROI were extracted and averaged for each participant. Finally, averaged t-values were entered into group-level one-sample t-tests to compare first-level observations to the null hypothesis with participants as a random effect.

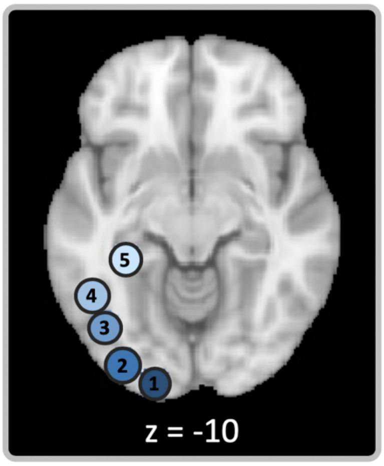


Figure 4.2. Location of ROIs used for univariate ROI analyses

Note. Colours and numbers correspond to ‘Key’ column in Table 4.1.

Table 4.1. *Source, location, and size of ROIs used for univariate ROI analyses*

Source	Location (AAL)	Hemisphere	Size (mm)	X	Y	Z	Key
Visual: All Words > Baseline	Inferior Occipital Cortex	Left	8	-18	-96	-9	①
Visual: All Words > Baseline	Inferior Occipital Cortex	Left	8	-33	-87	-9	②
Visual: All Words > Baseline	Inferior Occipital Cortex	Left	8	-42	-69	-9	③
Visual: All Words > Baseline	Inferior Temporal Gyrus	Left	8	-48	-54	-12	④
Taylor et al. (2013)	Parahippocampal Gyrus	Left	8	-32	-36	-12	⑤

Note. Source indicates where coordinates for each ROI were identified. AAL refers to Automated Anatomical Labelling. Key colours correspond to ROI locations depicted in Figure 4.2.

4.4. Representational Similarity Analysis

Representational Similarity Analysis (RSA) provides a framework for characterising and comparing representational geometries (Kriegeskorte & Kievit, 2013). RSA can be applied to fMRI data across multiple brain regions to compare the representational structure elicited by different stimuli to predicted models of similarity based on stimulus characterisations (Kriegeskorte et al., 2008). Crucially, this multivariate approach to analysing fMRI data advances our investigation beyond comparing levels of neural activation for different stimuli. Specifically, RSA enables us to decode patterns of neural activity and the type(s) of information being processed by different regions (Fischer-Baum, Bruggemann, Gallego, Li, & Tamez, 2017). For example, Fischer-Baum et al. (2017) inferred that, according to RSA logic, regions exhibiting similar patterns of neural activity for similar written items (e.g. DOUGH and TOUGH) process orthography as opposed to phonology or semantics. Had the investigation been restricted to univariate analysis of neural activity, Fischer-Baum et al. (2017) could not have determined whether a given brain region was involved in orthographic, phonological, or semantic processing, only whether it was activated by the presented stimuli. RSA enables us to go further than investigating neural activity, to understand not only if a given region is activated by a presented stimulus, but to characterise the nature of associated representations.

Searchlight RSA utilises a spherical volume to systematically investigate large regions within the brain. This form of RSA consists of six main stages (Rothlein & Rapp, 2014; see Figure 4.3). For each participant, a GLM approach is implemented to assess changes in neural activity in response to individual stimuli at each voxel in native space. First, a spherical searchlight is centred around one voxel and t-statistics associated with each voxel contained within the searchlight are recorded for each stimulus. Next, the dissimilarity between the voxel patterns for each pair of stimuli is computed as 1 minus the Pearson correlation across voxels which is then used to populate a neural Representational Dissimilarity Matrix (RDM; see Figure 4.3A for an illustration of constructing a neural RDM; Kriegeskorte et al., 2008). Crucially, use of the correlation distance at this stage separates RSA from the overall level of neural activation which consequently enables it to complement our univariate analyses (Kriegeskorte & Kievit, 2013). RDMs abstract from patterns of neural activity to characterise the similarity structure of neural responses to different stimuli and tend to be symmetrical along the diagonal comparing the same item to itself.

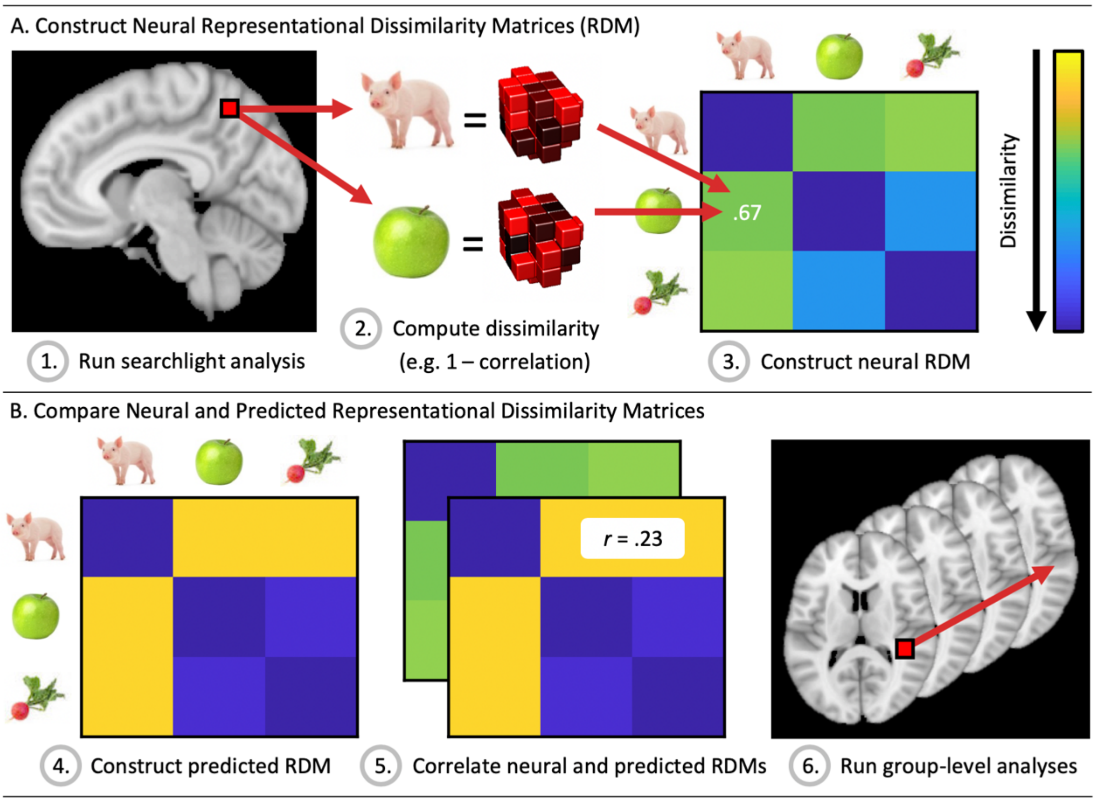


Figure 4.3. Illustration of the six stages of RSA. (A) A searchlight is centred around one voxel and t-statistics are extracted for all stimuli. Dissimilarity between all pairs of stimuli is computed as 1 minus the Pearson correlation across voxels to populate a neural RDM. (B) A predicted RDM is constructed using stimulus descriptions and correlated with the neural RDM to compare representations. Finally, group-level analyses are conducted to identify clusters with agreement across participants.

Fourth, a predicted RDM is constructed to characterise similarity based on stimulus descriptions (e.g., whether the meanings of pseudowords share the same semantic category), computational model representations, behaviour, etc. (Kriegeskorte & Kievit, 2013). Next, neural and predicted RDMs are correlated to determine the extent to which brain representations (patterns of activity) are explained by the predicted characteristic. The resulting correlation coefficient is assigned to the central voxel in the searchlight and the whole procedure is repeated for each voxel searchlight and participant. Finally, group-level one-sample t-tests are computed to identify clusters with agreement across participants. Figure 4.3B provides an illustration of correlating neural and predicted RDMs and conducting group-level analysis. The resulting t-map identifies brain regions where patterns of activity are significantly correlated with the predicted RDM (i.e., one-sample t-test against zero). Correlations between patterns of neural activity for the same set of stimuli and different predicted RDMs can be compared using voxel-wise paired-samples t-tests. Equally, correlations between patterns of activity for different sets of stimuli and the same or different predicted RDMs can also be compared using this approach.

We aimed to determine the type(s) of information being processed by different brain regions and explore potential differences in sensitivity to word similarity based on the orthographic transparency of trained writing systems. Searchlight RSA was conducted using the CoSMoMVPA toolbox (Oosterhof, Connolly, & Haxby, 2016) to identify regions where neural responses to spoken and written pseudowords were sensitive to phonemic, orthographic, and semantic similarity. First, a GLM approach was implemented to assess changes in neural activity in response to individual spoken and written pseudowords. GLMs were conducted using spatially and temporally realigned, unsmoothed, native space EPI images from each participant. For each modality and run, all events associated with each item were convolved with the canonical HRF to create regressors in the statistical model (*n* = 48; one per item within each writing system). Model parameters were otherwise identical to those described previously (see

'Univariate Analysis'). Voxel-wise contrast images were created for each participant and aimed to identify regions exhibiting activation for each item within each individual run compared to rest (i.e., bɛv > baseline), totalling 192 statistical maps per modality.

T-maps were chosen as the estimation of activation for RSA as effect sizes are weighted by error variances, which avoids large, highly variable, response estimates impacting on results (Taylor et al., 2019). Before performing RSA, t-statistics associated with each spoken and written item were averaged across runs for each participant, totalling 48 t-maps per modality. Next, neural RDMs were constructed using searchlight RSA. T-maps used to construct each neural RDM were normalised (mean-centred) by subtracting the mean value at each voxel. For each participant and voxel within their gray matter mask (see 'Pre-processing'), three neural RDMs were constructed per modality. To investigate neural sensitivity to word similarity across all spoken or written items, one matrix compared responses to all items from both writing systems ($n = 48$) to all items from the same writing system (comparisons between items from different systems were excluded). To investigate neural sensitivity to word similarity across spoken or written items from a single writing system, the remaining two matrices each compared all items from one writing system ($n = 24$). Each cell within a neural RDM represented 1 minus the Pearson correlation between t-statistics contained within a 100-voxel spherical searchlight centred around the same voxel for each item pair (Taylor et al., 2019).

To decode the informational content of different brain regions, neural RDMs were compared to several predicted RDMs (dissimilarity prediction matrices) based on the phonemic, orthographic, or semantic similarity of trained pseudowords (see Figure

4.4 for a summary of predicted RDMs). All predicted and neural RDMs were triangular due to symmetry along the diagonal and cells comparing the same item to itself were excluded as they inevitably predicted a perfect correlation (Rothlein & Rapp, 2014). Resulting correlation coefficients between the neural and predicted RDMs were returned to the central voxel of the searchlight to create a statistical map which was subsequently Fisher z-transformed to ensure correlations were normally distributed, a requirement for group-level parametric tests. Finally, all Fisher z-transformed correlation maps were co-registered to the participant's structural image (Ashburner & Friston, 1997), normalised to MNI space using a rigid-body transformation and the warping parameters used to normalise their structural image (see 'Pre-processing' for more details), and resampled to 3mm isotropic voxels.

Predictor RDMs

Predictor RDMs were constructed by computing the similarity between trained pseudowords from both writing systems based on phonemic, orthographic, and semantic characteristics. In Matrix 1, each cell represented 1 minus the proportion of same position phonemes shared between each item pair (Figure 4.4, row A). For example, /bɛv/ and /bʌv/ share 2/3 same position phonemes and were consequently represented by .33. In Matrix 2, each cell represented 1 minus the proportion of same position graphemes shared between each item pair (Figure 4.4, row B), and in Matrix 3 (Figure 4.4, row C) each cell represented whether the meanings of each item pair were from the same semantic category (same category = 0, different categories = 1).

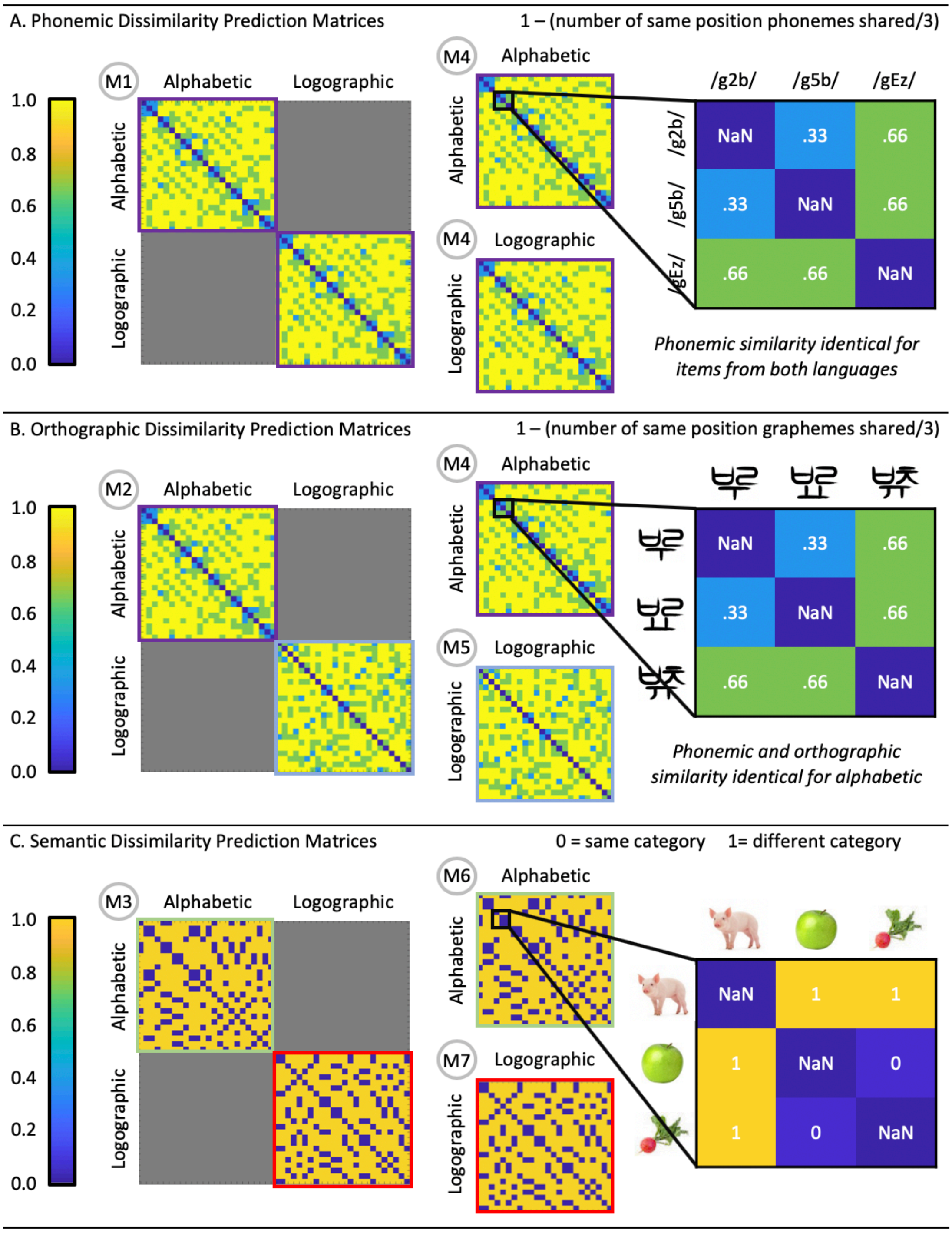


Figure 4.4. Summary of all predicted RDMs and how they were constructed. M refers to Matrix.

In Matrices 1 to 3, all items from both writing systems (n = 48) were compared to items from the same writing system. In contrast, Matrices 4 to 7 were designed to examine similarity structure independently for each trained writing system.

In Matrix 4 (Figure 4.4 rows A and B), each cell represented 1 minus the proportion of same position phonemes or graphemes shared between items from the alphabetic writing system, since this system featured regular one-to-one mappings between graphemes and phonemes. Matrix 4 also captured the proportion of same position phonemes shared between items from the logographic writing system because the CVC structure of items was equivalent to that of the alphabetic system (to facilitate counterbalancing between writing systems and participants). In Matrix 5, each cell represented 1 minus the proportion of same position graphemes shared between items from the logographic system (Figure 4.4, row B). Matrices 6 and 7 represented whether the meanings of items from the alphabetic or the logographic writing system were from the same category (Figure 4.4, row C). Note that, as the logographic system was formed by redistributing written pseudowords created using a regular one-to-one mapping between phonemes and graphemes to deliberately ensure similar spellings did not systematically share sounds (see ‘Stimuli’, chapter 2), predicted RDMs 4 and 5 were negatively correlated ($r = -.146$, $p = .015$). All predicted RDMs were used to compare word similarity to neural responses for all participants as counterbalanced phonological and orthographic scripts were entirely equivalent and interchangeable whether comprising an alphabetic or logographic writing system.

Group-level analyses

Normalised, Fisher z-transformed first-level RSA correlation maps were entered into group-level voxel-wise one-sample t-tests to identify clusters where patterns of neural activation were significantly correlated with prediction matrices across participants. Mean-centred accuracy scores from the Spelling and Vocabulary tasks (see chapter 3 for more details) were added as covariates to all one-sample t-tests to account for varying language abilities. The first set of analysis use Matrices 1 – 3 and looked for neural sensitivity to phonemic (Matrix 1), orthographic (Matrix 2), and semantic (Matrix 3) similarity across writing systems in each modality. Next, we looked for neural sensitivity to phonemic, orthographic, and semantic similarity within each writing system (Alphabetic/Logographic; Matrices 4 to 7). Importantly, Matrix 4 predicted neural sensitivity to either phonemic or orthographic similarity of items from the alphabetic writing system. Due to whole-word arbitrary mappings between spelling and sound, no equivalent first-level correlation maps existed for the logographic writing system. However, Matrix 4 and Matrix 5 predicted neural sensitivity to phonemic and orthographic similarity of items from the logographic system, respectively. Thus, for each participant, correlations between their neural RDM and Matrices 4 and 5 were added together at each voxel to generate a combined representation of neural sensitivity to either phonemic or orthographic similarity. The resulting first-level correlation maps were similarly compared to zero using voxel-wise one-sample t-tests (i.e., Logographic Matrix 4 and 5 > 0).

In addition, we aimed to identify brain regions that were only sensitive to the phonemic or orthographic similarity of items from one writing system. Thus, for each modality, voxels within the group-level t-map representing neural sensitivity to either phonemic or orthographic similarity of items from the logographic system were excluded from the equivalent first-level correlation maps for the alphabetic system (i.e., Alphabetic Matrix 4 masked > 0) and vice versa (i.e., Logographic Matrix 4 and 5 masked > 0) before conducting voxel-wise one-sample t-tests. Group-level paired-samples t-tests were also conducted at each voxel to identify brain regions where representations of spoken or written items were more phonemically (Alphabetic Matrix 4 vs. Logographic Matrix 4), orthographically (Alphabetic Matrix 4 vs. Logographic Matrix 5), phonemically/orthographically (Alphabetic Matrix 4 vs. Logographic Matrix 4 and 5), or semantically (Alphabetic Matrix 6 vs Logographic Matrix 7) structured when associated with different writing systems.

Finally, we aimed to identify brain regions exhibiting sensitivity to word similarity across both visual and auditory modalities. Voxel-wise conjunction analysis was performed on group-level t-maps representing neural sensitivity to the phonemic/ orthographic (Visual Alphabetic Matrix 4 > 0 x Auditory Alphabetic Matrix 4 > 0) or semantic (Visual Alphabetic Matrix 6 > 0 x Auditory Alphabetic Matrix 6 > 0) similarity of written and spoken alphabetic pseudowords. Equivalent analyses were conducted to identify brain regions exhibiting sensitivity to the phonemic (Visual Logographic Matrix 4 > 0 x Auditory Logographic Matrix 4 > 0), orthographic (Visual Logographic Matrix 5 > 0 x Auditory Logographic Matrix 5 > 0), phonemic/orthographic (Visual Logographic Matrix 4 and 5 > 0 x Auditory Logographic Matrix 4 and 5 > 0), and semantic (Visual Logographic Matrix 7 > 0 x Auditory Logographic Matrix 7 > 0) similarity of logographic pseudowords.

Voxels located outside MNI space following normalisation were removed and all group-level results were thresholded at voxel-wise FWE corrected $p < .05$. In addition, statistical maps resulting from one-sample and paired-samples t-tests were Threshold-Free Cluster Enhanced (TFCE; Smith & Nichols, 2009) using a toolbox integrated into SPM12 (Gaser, 2013; Structural Brain Mapping Group, Jena University Hospital, www.neuro.uni-jena.de/tfce). TFCE aims to enhance voxel-wise sensitivity by replacing each t-statistic with a weighted average based on neighbouring voxels. This method was combined with voxel-wise Monte-Carlo simulation (i.e., non-parametric refinement of p-values) using 10,000 permutations to transform statistical maps into uncorrected p-values. As it was not possible to perform conjunction analysis using the previous toolbox, statistical maps resulting from conjunction analyses were TFCE enhanced using a pTFCE toolbox (Spisák et al., 2019) similarly integrated into SPM12. Consequently, TFCE was conducted without permutation testing and therefore constituted a parametric approach.

Region of Interest (ROI) analysis

ROI analyses were conducted on whole-brain correlation maps using MarsBaR to visualise and compare group-level RSA results and maximise sensitivity within predefined brain regions. 8mm spherical ROIs were created within brain regions associated with visual processing, orthography to phonology conversion, and spoken language and semantic processing using MarsBaR. ROIs were defined within the left hemisphere and generalised to identify coordinates and create ROIs in the right.

Five visual processing ROIs were constructed using peak neural activations from the univariate group-level contrast all items > baseline for Visual Semantic Monitoring. Selection was guided by coordinates from Vinckier et al. (2007). The four most posterior ROIs were also used to conduct univariate ROI analysis (see Figure 4.2). Here, coordinates for left anterior fusiform were taken from Taylor et al. (2013) as univariate ROI analyses aimed to examine whether neural activity along left vOT shifted from being greater for alphabetic than logographic written pseudowords. In contrast, RSA analyses aimed to examine neural sensitivity to word similarity in regions associated with visual processing. Thus, the most anterior ROI was not replaced with an overlapping ROI defined using coordinates from Taylor et al. (2013) as those from Vinckier et al. (2007) were considered to be more theoretically driven. Figure 4.5 shows the location of our visual processing ROIs and Table 4.2 provides additional details including their source, anatomical label, and coordinates.

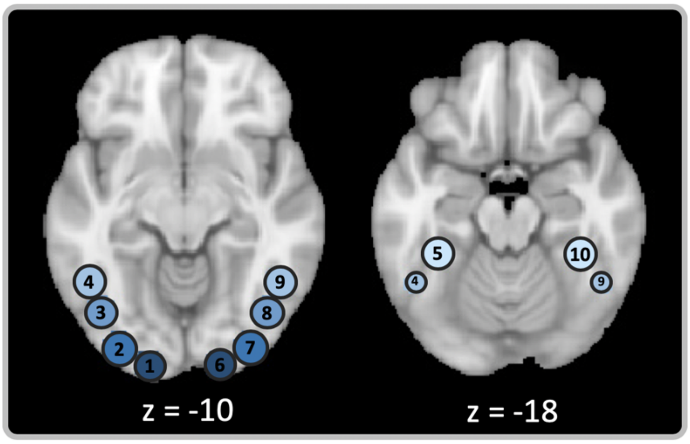


Figure 4.5. Location of visual processing ROIs for RSA correlation maps

Note. Colours and numbers correspond to ‘Key’ column within Table 4.2.

Table 4.2. *Source, location, and size of visual processing ROIs for RSA correlation maps*

Source	Location (AAL)	Hemisphere	Size (mm)	X	Y	Z	Key
Visual: All Words > Baseline	Inferior Occipital Cortex	Left	8	-18	-96	-9	①
Visual: All Words > Baseline	Inferior Occipital Cortex	Left	8	-33	-87	-9	②
Visual: All Words > Baseline	Inferior Occipital Cortex	Left	8	-42	-69	-9	③
Visual: All Words > Baseline	Inferior Temporal Gyrus	Left	8	-48	-54	-12	④
Visual: All Words > Baseline	Fusiform Gyrus	Left	8	-36	-39	-21	⑤
Visual: All Words > Baseline	Inferior Occipital Cortex	Right	8	18	-96	-9	⑥
Visual: All Words > Baseline	Inferior Occipital Cortex	Right	8	33	-87	-9	⑦
Visual: All Words > Baseline	Inferior Occipital Cortex	Right	8	42	-69	-9	⑧
Visual: All Words > Baseline	Inferior Temporal Gyrus	Right	8	48	-54	-12	⑨
Visual: All Words > Baseline	Fusiform Gyrus	Right	8	36	-39	-21	⑩

Note. Source indicates where coordinates for each ROI were identified. AAL refers to Automated Anatomical Labelling. Key colours correspond to ROI locations depicted in Figure 4.5.

Coordinates for left Inferior Parietal Lobule (IPL) were identified using our group-level contrast all items > baseline for Visual Semantic Processing as this brain region has been associated with conversion of orthography to phonology. Peak activation coordinates closest to IPL coordinates taken from Taylor et al. (2013) were selected for the analyses. Figure 4.6 shows the location of our IPL ROIs; Table 4.3 provides additional details including their source, anatomical label, and coordinates.

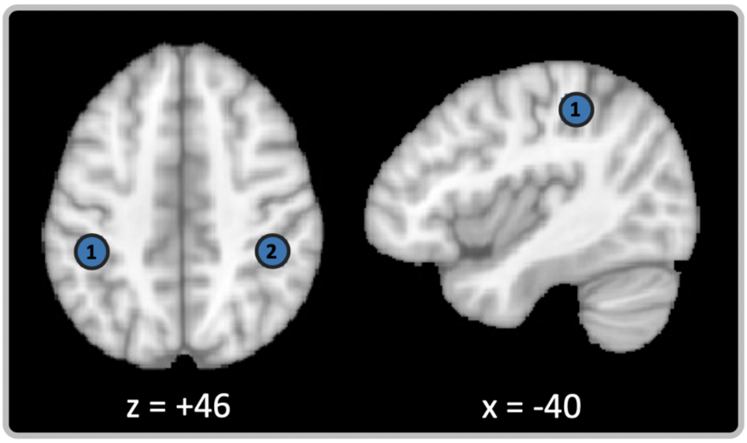


Figure 4.6. Location of Inferior Parietal Lobule ROIs for RSA correlation maps

Note. Numbers correspond to the 'Key' column within Table 4.3.

Table 4.3. *Source, location, and size of Inferior Parietal Lobule ROIs for RSA correlation maps*

Source	Location (AAL)	Hemisphere	Size (mm)	X	Y	Z	Key
Visual: All Words > Baseline	Inferior Parietal Lobule	Left	8	-42	-36	48	①
Visual: All Words > Baseline	Inferior Parietal Lobule	Left	8	42	-36	48	②

Note. Source indicates where coordinates for each ROI were identified. AAL refers to Automated Anatomical Labelling. Key colours correspond to ROI locations depicted in Figure 4.6.

Three ROIs were defined within brain regions associated with spoken language processing (see Davis & Gaskell, 2009). Coordinates for these regions were selected from peak neural activations within our group-level contrast all items > baseline for Auditory Semantic Monitoring and defined using Automated Anatomical Labelling. Figure 4.7 shows the location of our spoken language processing ROIs; Table 4.4 provides additional details including their source, anatomical label, and coordinates.

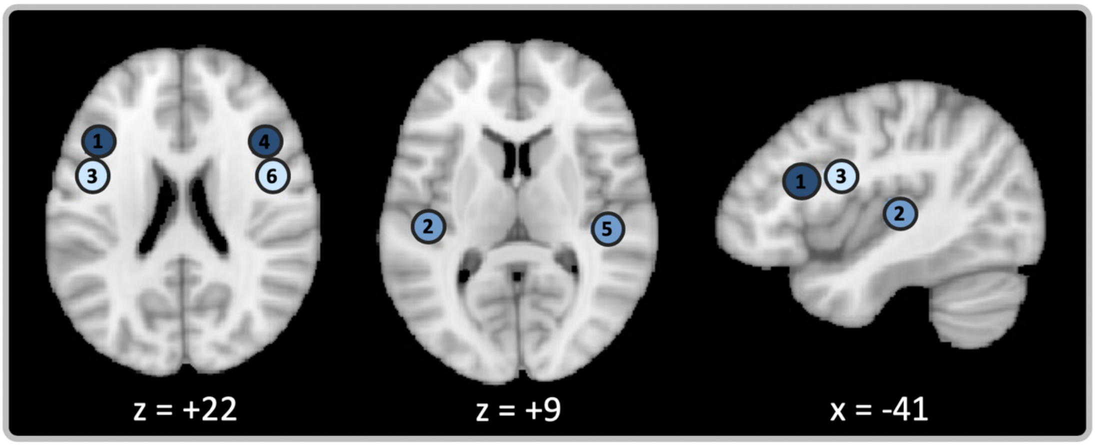


Figure 4.7. Location of spoken language processing ROIs for RSA correlation maps

Note. Colours and numbers correspond to the 'Key' column within Table 4.4.

Table 4.4. *Source, location, and size of spoken language processing ROIs for RSA correlation maps*

Source	Location (AAL)	Hemisphere	Size (mm)	X	Y	Z	Key
Auditory: All Words > Baseline	Inferior Frontal Gyrus	Left	8	-42	21	21	①
Auditory: All Words > Baseline	Superior Temporal Gyrus	Left	8	-45	-24	6	②
Auditory: All Words > Baseline	Precentral Gyrus	Left	8	-45	3	24	③
Auditory: All Words > Baseline	Inferior Frontal Gyrus	Right	8	42	21	21	④
Auditory: All Words > Baseline	Superior Temporal Gyrus	Right	8	45	-24	6	⑤
Auditory: All Words > Baseline	Precentral Gyrus	Right	8	45	3	24	⑥

Note. Source indicates where coordinates for each ROI were identified. AAL refers to Automated Anatomical Labelling. Key colours correspond to ROI locations depicted in Figure 4.7.

Two ROIs associated with semantic processing were taken directly from Taylor et al. (2013) as no equivalent peak coordinates existed within our group-level contrast all items > baseline for either modality. These sets of coordinates were moved by

2mm to avoid overlap between the resulting ROIs. A third set of coordinates for left anterior fusiform (-36 -39 -21) was the same as the most anterior visual processing ROI. Figure 4.8 shows the location of our semantic processing ROIs and Table 4.5 provides additional details including their source, anatomical label, and coordinates.

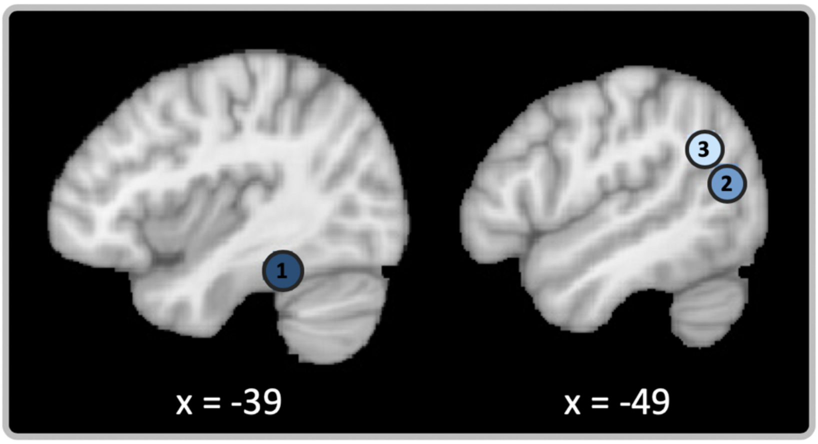


Figure 4.8. Location of semantic processing ROIs for RSA correlation maps

Note. Colours and numbers correspond to 'Key' column within Table 4.5.

Table 4.5. *Source, location, and size of semantic processing ROIs for RSA correlation maps*

Source	Location (AAL)	Hemisphere	Size (mm)	X	Y	Z	Key
Visual: All Words > Baseline	Fusiform Gyrus	Left	8	-36	-39	-21	①
Taylor et al. (2013)	Middle Temporal Gyrus	Left	8	-48	-66	16	②
Taylor et al. (2013)	Angular Gyrus	Left	8	-52	-56	30	③
Visual: All Words > Baseline	Fusiform Gyrus	Right	8	36	-39	-21	④
Taylor et al. (2013)	Middle Temporal Gyrus	Right	8	48	-66	16	⑤
Taylor et al. (2013)	Angular Gyrus	Right	8	52	-56	30	⑥

Note. Source indicates where coordinates for each ROI were identified. AAL refers to Automated Anatomical Labelling. Key colours correspond to ROI locations depicted in Figure 4.8.

For each correlation map representing neural sensitivity to phonemic, orthographic, or semantic similarity of spoken or written pseudowords from one writing system, correlations from voxels within each ROI were extracted and averaged for each participant. Averaged correlations associated with each ROI were then entered into paired-samples t-tests to identify brain regions where representations of spoken or written items were more phonemically, orthographically, or semantically structured when associated with different writing systems (i.e., alphabetic > logographic, and vice versa). ROI analyses were only conducted to compare writing systems, not to look at correlations across or within each writing system relative to zero.

CHAPTER V: NEUROIMAGING RESULTS

The present study investigated how the orthographic transparency of a writing system impacts on spoken language systems and reading acquisition. We implemented an artificial language paradigm supported by fMRI measures of brain activity to test how alphabetic and logographic writing systems differentially influence neural activation and the underlying representations of adults learning to read novel orthographies. Participants learned to read two artificial languages with alphabetic and logographic writing systems. Following training, they were engaged in two fMRI scanning sessions, in which they were tasked to monitor the meanings of trained spoken (*Auditory Semantic Monitoring*) and written (*Visual Semantic Monitoring*) pseudowords (see Figure 4.1 in chapter 4 for a summary of scanning protocols). Auditory semantic monitoring involved recall of meaning from sound and enabled us to investigate orthographic effects on spoken language processing by comparing neural activation and the nature of underlying representations. Visual semantic monitoring involved retrieving meaning from spelling and was used to determine how the nature of a writing system impacts on the “division of labour” between dorsal (orthography-phonology; O-P) and ventral (orthography-semantics; O-S) pathways of the reading network (Plaut et al., 1996) and written language representations.

We hypothesised that the orthographic transparency of a writing system will determine the existence of orthographic effects on spoken language processing, the division of labour between dorsal and ventral reading pathways (Plaut et al., 1996), and neural sensitivity to phonemic, orthographic, and semantic similarity during listening and reading. Our predictions about how a writing system impacts on spoken language processing and reading acquisition are predicated on the relationship between sound and spelling. As transparent alphabetic writing systems feature consistent, one-to-one mappings between sounds and symbols, we predicted that spoken language processing will be uniquely impacted via phonological restructuring or orthographic co-activation (Smith et al., 2021) and that spoken language representations will exhibit greater sensitivity to phonemic and orthographic similarity than opaque logographic writing systems. Equally, due to the systematic nature of alphabetic orthographies, we predicted that sub-word spelling-sound information will be favoured during reading, strengthening O-P mappings, increasing reliance on the dorsal pathway, and similarly increasing neural sensitivity to phonemic and orthographic similarity.

As opaque logographic writing systems lack O-P systematicity (instead featuring whole-word mappings between sounds and spellings), we predict spoken language processing will not be impacted by reading acquisition and that spoken language representations will only exhibit sensitivity to phonemic and not orthographic similarity. Equally, due to the arbitrary nature of spelling-sound mappings, we predicted that O-S mappings will be favoured during reading, increasing reliance on the ventral pathway as the more efficient mapping (Seidenberg, 2011), and that representations will only be sensitive to orthographic and not phonemic similarity. Further, we expect neural representations to be sensitive to the semantic similarity of alphabetic and logographic spoken and written words. Nevertheless, our behavioural findings indicated that, while the alphabetic writing system favoured systematic O-P mappings, the logographic system favoured arbitrary O-S mappings during reading acquisition. Thus, we predict that spoken and written language representations will be more sensitive to the semantic similarity of logographic than alphabetic words.

Spelling-sound convergence has been found in many cortical brain regions with limited variation between different languages (e.g., Rueckl et al., 2015; Chyl et al., 2019). Thus, we predict that alphabetic and logographic writing systems will exhibit convergent neural activity for spoken and written language in similar regions. Moreover, representations are predicted to be sensitive to the phonemic/orthographic similarity of alphabetic spoken and written words in similar regions associated with phonological processing. As we predicated that representations will only exhibit sensitivity to the phonemic similarity of logographic spoken words and the orthographic similarity of logographic written words, we do not expect any representations to be sensitive to the phonemic or orthographic similarity of both spoken and written logographic words. Finally, representations are expected to be sensitive to the semantic structure of spoken and written words from the alphabetic and logographic systems in similar regions associated with semantic processing.

Univariate contrasts identified brain regions activated by alphabetic and logographic spoken and written words and enabled us to assess which, if any, regions were more engaged by words from one language than the other. These analyses were conducted to address our hypotheses concerning orthographic effects on spoken language and how the nature of the writing system impacts on the division of labour between dorsal and ventral reading pathways. In addition, region of interest (ROI) analysis maximised sensitivity and specificity to examine a shift from neural activation being greater for alphabetic > logographic to logographic > alphabetic written words along the left posterior to anterior occipitotemporal cortex (vOT; see Taylor et al., 2013). Further, Representational Similarity Analysis (RSA) furthered our investigation beyond levels of neural activity by understanding how the nature of the writing system impacts on underlying representations. Implementing this multivariate approach enabled us to decode the informational content of different regions by making conclusions about processing based on neural sensitivity to measures of word similarity (Kriegeskorte et al., 2008). RSA addressed our predictions about whether and how orthographic transparency impacts on neural sensitivity to phonemic, orthographic, and semantic similarity. Finally, conjunction analysis identified brain regions exhibiting spelling-sound convergence and convergent neural sensitivity to the phonemic, orthographic, and semantic similarity of alphabetic and logographic spoken and written words.

Univariate analyses are presented for auditory and visual modalities; these analyses include ROI and conjunction analyses. Following the presentation of univariate analyses, RSA results are similarly presented for auditory and visual modalities. These analyses also include ROI and conjunction analyses. All materials, data and analysis scripts can be found in the OSF storage for this project: https://osf.io/3q2jb/.

5.1. Univariate Analysis

Auditory semantic monitoring

Due to the systematic relationship between spelling and sound, we predicted that regions associated with orthographic processing will be active for alphabetic spoken words, while regions associated with phonological and semantic processing will be active for alphabetic and logographic spoken words. To identify brain regions engaged by spoken language, we compared neural activity elicited by all spoken alphabetic and logographic words, combined and separately, relative to rest using voxel-wise one-sample t-tests. Results are presented in Figure 5.1 and all slices and peak coordinates are available on the OSF. Contrasting all spoken words from both languages > baseline revealed activity in left inferior frontal and bilateral superior temporal regions including left inferior frontal gyrus (triangularis and opercularis), insula and thalamus, right transverse temporal gyrus, hippocampus, middle cingulate cortex, cerebellum and supplementary motor area, and bilateral superior temporal gyri, caudate nucleus and precuneus (see Figure 5.1A). The statistical contrast alphabetic > baseline revealed activity in similar frontal and temporal regions including left inferior frontal gyrus (triangularis), hippocampus, posterior cingulate cortex, rolandic operculum, thalamus and precentral gyrus, right transverse temporal gyrus, precuneus, and cerebellum, and bilateral inferior frontal gyri (opercularis), superior temporal gyri, caudate nucleus, middle cingulate cortex, insula, and supplementary motor area (see Figure 5.1B). The statistical contrast logographic > baseline again revealed similar brain regions including left inferior frontal gyrus (triangularis), precuneus, posterior cingulate cortex, rolandic operculum, thalamus, and precentral gyrus, right transverse temporal gyrus and cerebellum, and bilateral inferior frontal gyri (opercularis), superior temporal gyri, hippocampus, caudate nucleus, middle cingulate cortex, insula, and supplementary motor area (see Figure 5.1C). Crucially, while no evidence of online co-activation of orthographic representations was observed during spoken language processing, these results validate our method as regions associated with phonological and semantic processing were activated by trained spoken pseudowords.

To evaluate our prediction that brain regions associated with phonological and orthographic processing would be more active for alphabetic spoken words, we contrasted activity elicited by spoken alphabetic and logographic words using voxel-wise paired-samples t-tests. The statistical contracts alphabetic > logographic and

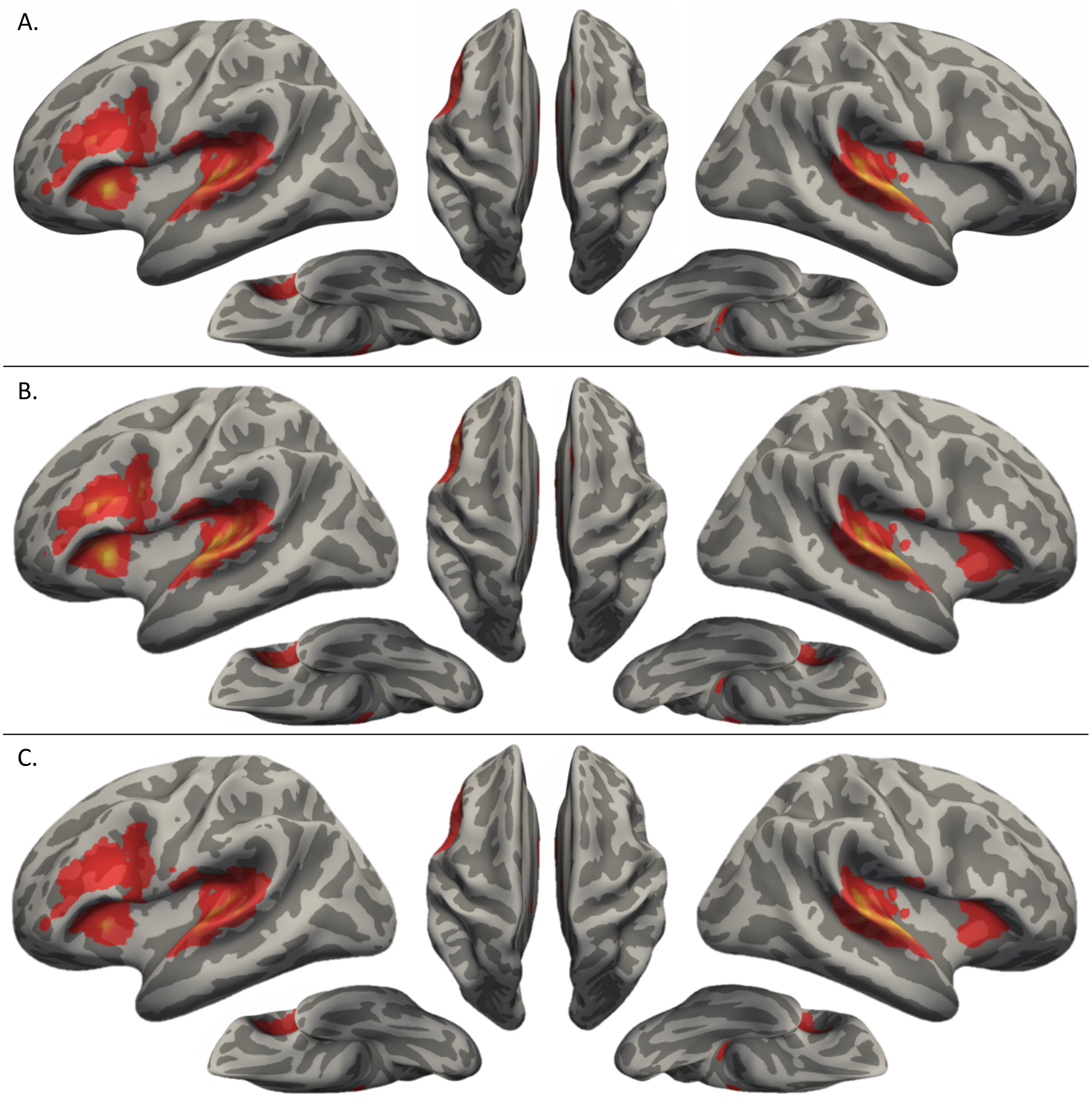


Figure 5.1. Univariate activation when retrieving the meaning of (A) all trained spoken pseudowords > baseline, (B) alphabetic spoken pseudowords > baseline, and (C) logographic spoken pseudowords > baseline. Results are thresholded at $p < .001$ voxel-wise uncorrected, $p < .05$ FWE cluster corrected. Statistical maps are projected onto both segmented and inflated template brain anatomies.

logographic > alphabetic revealed no significant voxels at $p < .001$ voxel-wise uncorrected and $p < .05$ FWE cluster corrected, indicating that no brain regions were more active for one writing system than the other. Overall, these analyses support our prediction that regions associated with phonological and semantic processing will be active when participants recall the meaning of alphabetic and logographic spoken words. However, our predictions that regions associated with orthographic processing will be active for alphabetic spoken words and regions associated with phonological and orthographic processing will be more active for the alphabetic language are unsupported. Thus, consistent with our behavioural findings, these univariate neuroimaging analyses do not support our hypothesis that the orthographic transparency of the writing system will impact on spoken language processing.

Visual semantic monitoring

As alphabetic writing systems feature systematic relations between graphemes and phonemes, we predicted alphabetic words would activate regions involved in semantic processing via the indirect dorsal reading pathway (Plaut et al., 1996). In contrast, we predicted the logographic writing system would compensate for more arbitrary spelling-sound mappings by activating regions associated with semantic processing via the direct ventral pathway, with less involvement from regions associated with phonological processing. To identify brain regions engaged by written language, we compared activity elicited by all written alphabetic and logographic words, combined and separately, relative to rest using voxel-wise one-sample t-tests. Contrasting all written words from both writing systems > baseline revealed left lateralised activation of inferior frontal and parietal regions and bilateral inferior occipital and temporal lobe, including vOT. These regions included left inferior frontal gyrus (triangularis), middle and inferior temporal gyri, superior parietal lobule, putamen, and precentral gyrus, right superior occipital gyrus, and calcarine sulcus, and bilateral fusiform gyri, inferior parietal lobule, middle and inferior occipital gyri, hippocampus, insula, thalamus, cerebellum, and supplementary motor area (see Figure 5.2A).

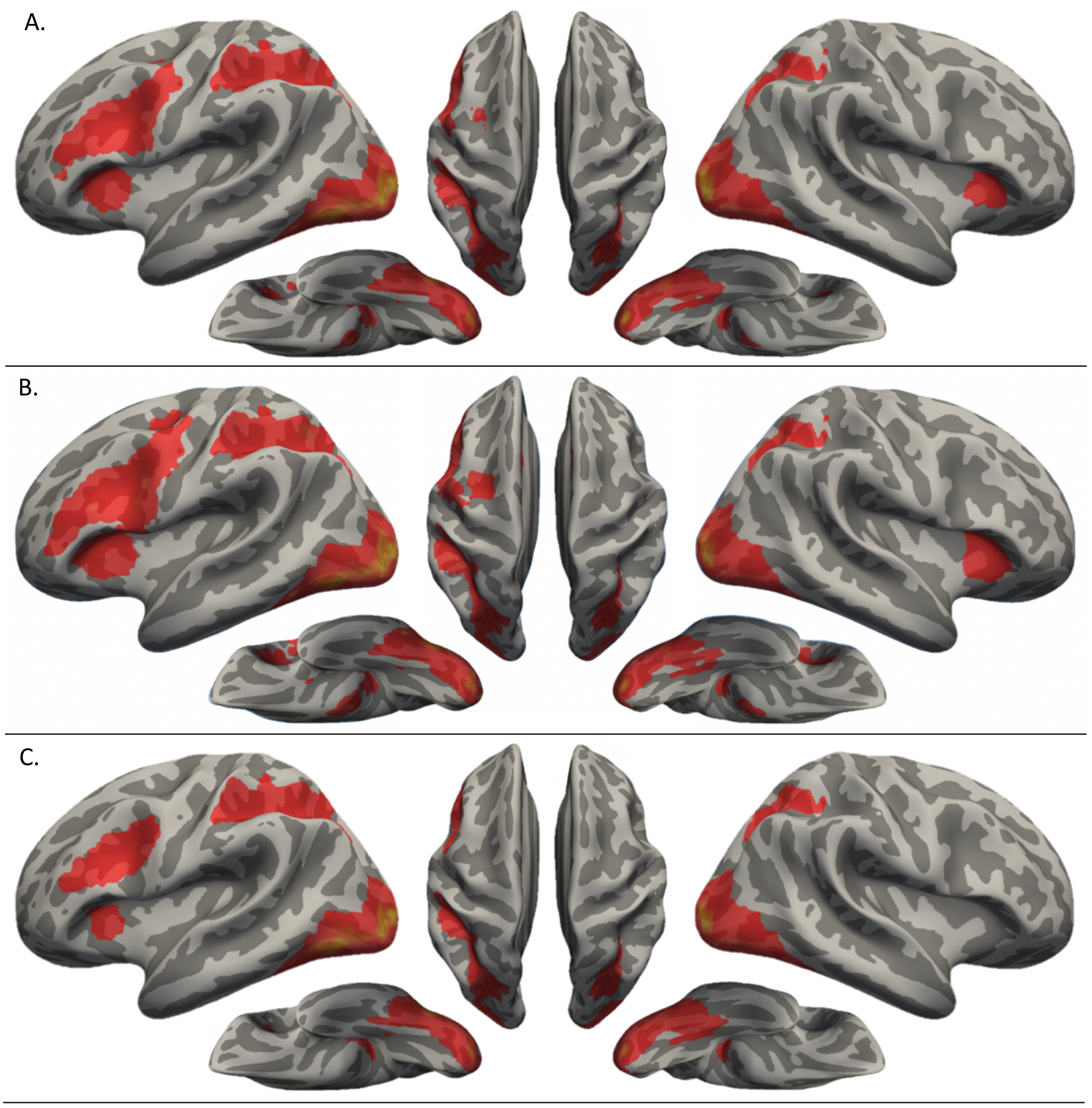


Figure 5.2. Univariate activation when retrieving the meaning of (A) all trained written pseudowords > baseline, (B) alphabetic written pseudowords > baseline, and (C) logographic written pseudowords > baseline. Results are thresholded at $p < .001$ voxel-wise uncorrected, $p < .05$ FWE cluster corrected. Statistical maps are projected onto both segmented and inflated template brain anatomies.

The statistical contrast alphabetic > baseline revealed activity in similar regions including left inferior frontal gyrus (triangularis), inferior temporal gyrus, fusiform gyrus, lingual gyrus, caudate nucleus, putamen, and precentral gyrus, right inferior frontal gyrus (opercularis), calcarine sulcus, hippocampus, and insula, and bilateral superior parietal lobule, inferior parietal lobule, superior occipital gyri, middle occipital gyri, inferior occipital gyri, thalamus, cerebellum, and supplementary motor area (see Figure 5.2B). The statistical contrast logographic > baseline revealed similar brain regions with less pronounced left lateralised inferior frontal activation. These regions included left middle and inferior frontal gyri (triangularis), middle temporal gyrus, inferior parietal lobule, insula, and precentral gyrus, right angular gyrus, superior occipital gyrus, calcarine sulcus and thalamus, and bilateral fusiform gyri, superior parietal lobule, middle and inferior occipital gyri, hippocampus, cerebellum, and supplementary motor area (see Figure 5.2C). While the dorsal pathway was active for both writing systems, these analyses validate our method as all trained written pseudowords activated regions associated with visual and orthographic processing.

We hypothesised that brain regions associated with orthographic and phonological processing along the dorsal reading pathway will be more active for alphabetic written words, while regions associated with lexical-semantic processing along the ventral pathway will be more active for logographic written words. To evaluate these hypotheses, we contrasted neural activity elicited by alphabetic and logographic written words using voxel-wise paired-samples t-tests. The statistical contrast alphabetic > logographic revealed greater activity along the dorsal pathway including left superior frontal gyrus, inferior frontal gyrus (triangularis and opercularis), inferior parietal lobule, postcentral gyri, inferior temporal gyrus, caudate nucleus, insula, and thalamus, right cerebellum, and bilateral precentral gyri and supplementary motor area (see Figure 5.3A). The statistical contrast logographic > alphabetic revealed greater activity in left lateralised superior frontal and bilateral occipito-parietal regions including left superior frontal gyrus, middle frontal gyrus, inferior parietal lobule, angular gyrus, and middle cingulate gyrus, right parahippocampal gyrus, and bilateral middle temporal gyri, middle occipital gyri, and precuneus (see Figure 5.3B).

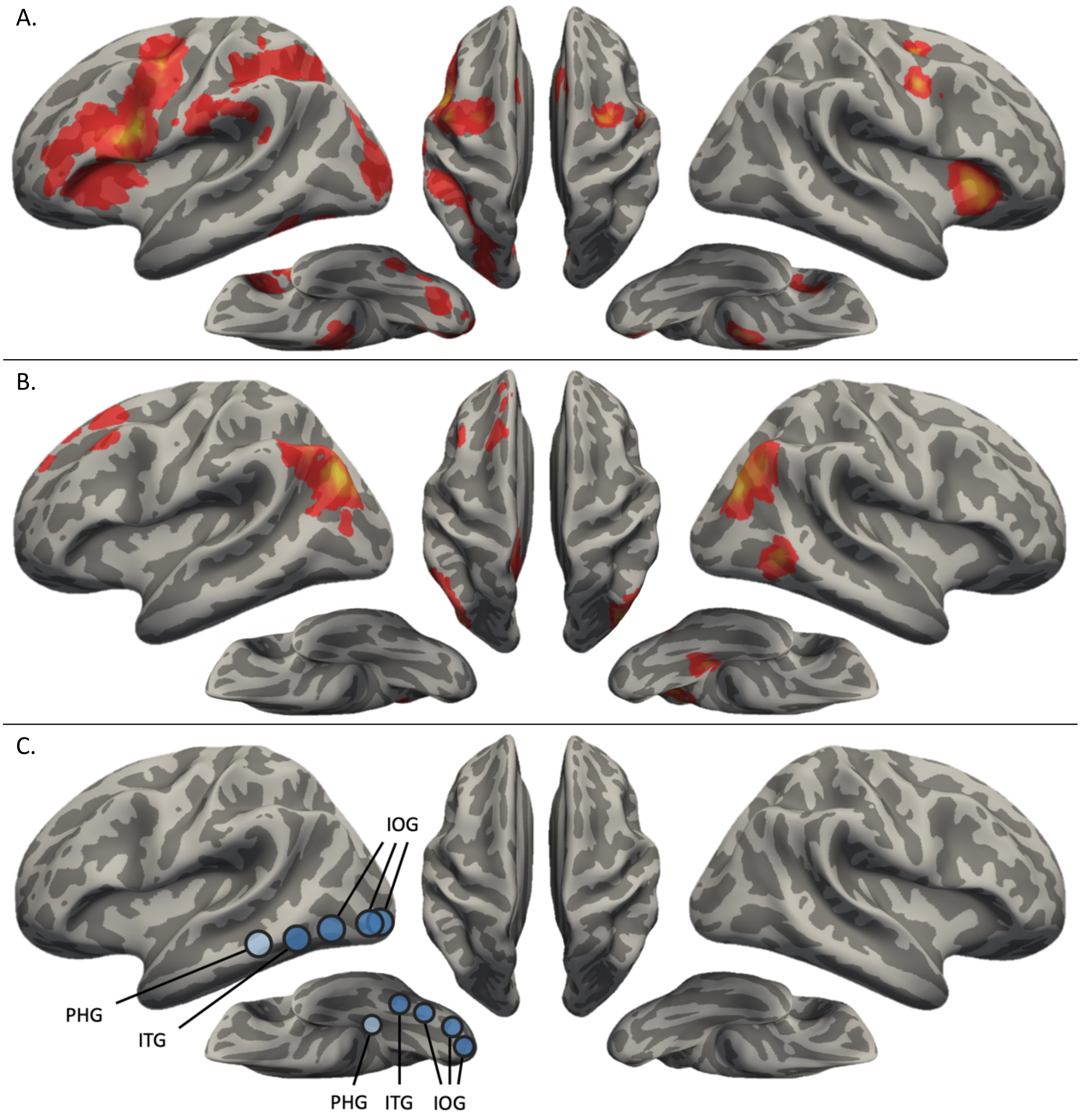


Figure 5.3. Univariate activation when retrieving the meaning of (A) alphabetic > logographic written pseudowords and (B) logographic > alphabetic written pseudowords. Results are thresholded at $p < .001$ voxel-wise uncorrected, $p < .05$ FWE cluster corrected. (C) Locations of 8mm ROIs used for univariate analyses. Dark and light blue discs represent ROIs exhibiting greater activation for alphabetic > logographic written items and vice versa, respectively ($p < .05$ without Bonferroni correction). PHG, parahippocampal gyrus; ITG, inferior temporal gyrus; IOG, inferior occipital gyrus. Statistical maps and ROIs are projected onto segmented, inflated template brain anatomies.

These analyses support our prediction that participants will capitalise on systematic mappings between spelling and sound when reading alphabetic words, strengthening O-P mappings, and increasing reliance on the dorsal reading pathway. Further, they support our prediction that the logographic system will compensate for more arbitrary spelling-sound mappings, favouring O-S mappings, and increasing reliance on the ventral pathway. While the logographic writing system also activated regions along the dorsal pathway, posterior regions along the ventral pathway including left anterior vOT exhibited greater activity compared to the alphabetic system. Combined, these findings are consistent with our behavioural results which indicated that the alphabetic system capitalised on systematic, componential O-P mappings while the logographic system favoured arbitrary, holistic O-S mappings during reading acquisition.

Region of Interest (ROI) analysis

Taylor et al. (2019) and Vinckier et al. (2007) described a processing hierarchy along posterior to anterior vOT; activation was greater for pseudowords > words in posterior vOT and words > pseudowords in anterior vOT. Alphabetic writing systems should facilitate the same fine-grained analysis of grapheme to phoneme mappings that characterises pseudoword reading. Logographic writing systems should encourage whole-word analysis associated with known word reading. Thus, we predicted a shift from greater activation for alphabetic > logographic to logographic > alphabetic written words along left posterior to anterior vOT. Equally, such a finding would lend further support to our prediction that logographic systems will increase reliance on the ventral reading pathway. To evaluate this prediction while maximising sensitivity and specificity, we conducted ROI analyses. Here, we performed one-sample t-tests to identify regions exhibiting greater neural activity for either writing system using first-level alphabetic > logographic statistical contrasts. Figure 5.3C (p. 142) depicts the location of five ROIs and whether they elicited greater activity for alphabetic or logographic written words. Results are presented in Figure 5.4 and Table 5.1 provides additional details including anatomical labels, coordinates, and statistics.

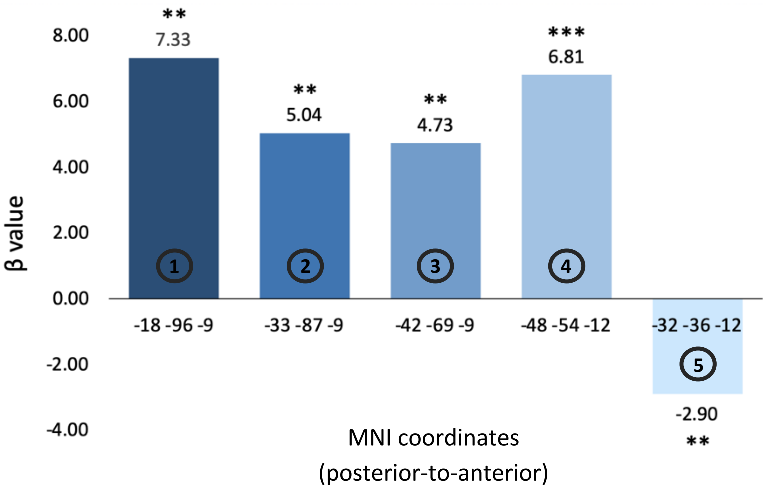


Figure 5.4. Statistics Associated with Univariate ROI Analyses of Neural Activation Elicited by Alphabetic and Logographic Written Pseudowords Using an Alphabetic > Logographic Contrast

Note. Univariate activation within left posterior-to-anterior vOT ROIs when retrieving meanings of alphabetic compared to logographic written pseudowords. *β* represents the effect size for each paired-samples *t*-test implementing an alphabetic > logographic contrast. *p*-values are not Bonferroni corrected; <.001 = ***, <.01 = **, <.05 = *. Bar colours and numbers correspond to numbered discs within Table 5.1 below and Figure 4.2 and Table 4.1 (see chapter 4, 'Neuroimaging Methods').

Table 5.1. *Location, Size, and Statistics Associated with Univariate ROI Analyses of Neural Activation Elicited by Written Pseudowords Using an Alphabetic > Logographic Contrast*

Location (AAL)	Hemisphere	Size (mm)	X	Y	Z	*β*	*t*	*p*	Key
Inferior Occipital Cortex	Left	8	-18	-96	-9	7.33	3.22	.002	①
Inferior Occipital Cortex	Left	8	-33	-87	-9	5.04	3.30	.002	②
Inferior Occipital Cortex	Left	8	-42	-69	-9	4.73	2.55	.009	③
Inferior Temporal Gyrus	Left	8	-48	-54	-12	6.81	3.81	<.001	④
Parahippocampal Gyrus	Left	8	-32	-36	-12	-2.90	-3.63	.001	⑤

Note. AAL refers to Automated Anatomical Labelling. *β* represents the effect size associated with each paired-samples *t*-test implementing an alphabetic > logographic contrast. *p*-values are not Bonferroni corrected. Key colours and numbers correspond to bars within Figure 5.4 and the same numbered discs located within Figure 4.2 and Table 4.1 (see chapter 4, 'Neuroimaging Methods').

Neural activity elicited by written words shifted from being greater for alphabetic > logographic in the four most posterior ROIs (i.e., left posterior and anterior inferior occipital gyrus, posterior fusiform gyrus, and inferior temporal gyrus) to logographic > alphabetic in left parahippocampal gyrus (the most anterior ROI). These analyses support our prediction that opaque logographic writing systems will increase reliance on the ventral reading pathway and, more specifically, that neural activity will shift from being greater for alphabetic > logographic to logographic > alphabetic words.

Conjunction analysis between visual and auditory modalities

Convergent activity has been found for spoken and written language in various brain regions, with limited variation between languages with transparent and opaque writing systems (e.g., Rueckl et al., 2015; Chyl et al., 2019). Thus, we hypothesised that trained alphabetic and logographic writing systems will exhibit spelling-sound convergence in similar regions (including left inferior frontal gyri, middle to superior temporal gyri, and inferior parietal lobule). To evaluate this prediction, we performed conjunction analysis on group-level t-maps resulting from one-sample t-tests aiming to identify regions with greater activity for spoken and written words from alphabetic (alphabetic > baseline) and logographic (logographic > baseline) writing systems than rest. The statistical contrast alphabetic > baseline revealed convergent neural activity for spoken and written pseudowords in left lateralised inferior frontal regions. These regions included left inferior frontal gyrus (triangularis) and precentral gyrus, right hippocampus, caudate nucleus, thalamus, and cerebellum, and bilateral inferior frontal gyri (opercularis), insula, and supplementary motor area (see Figure 5.5A). The statistical contrast logographic > baseline revealed speech-print convergence in

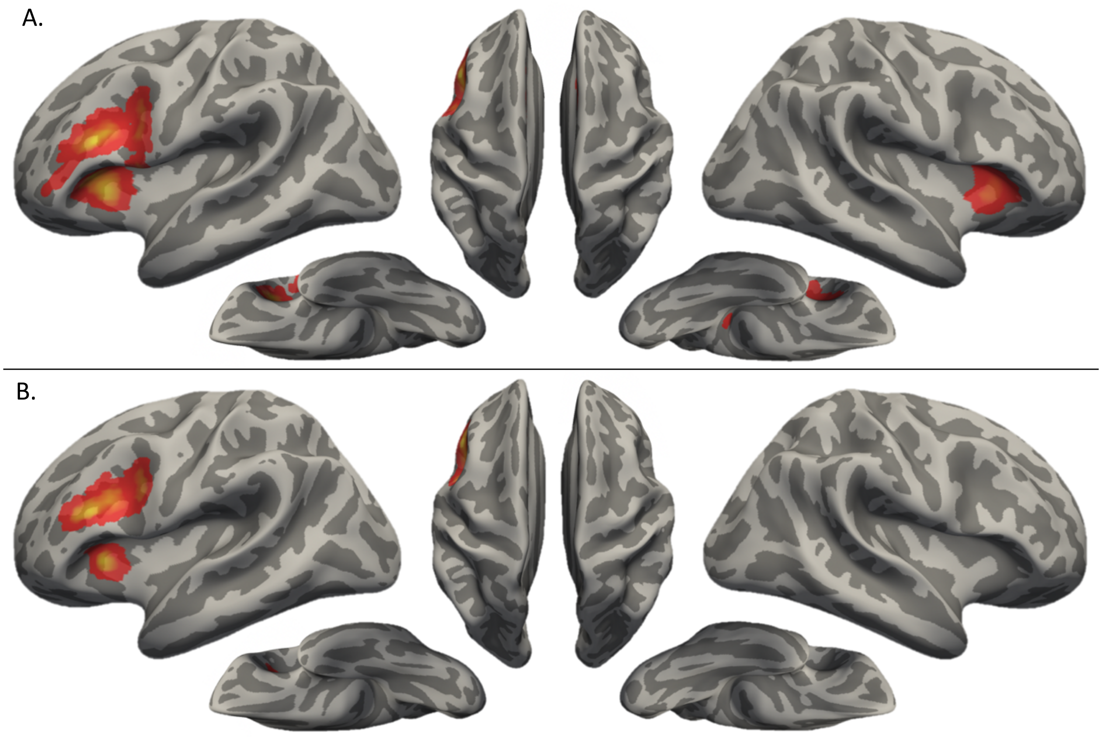


Figure 5.5. Shared univariate activation when retrieving the meaning of both (A) alphabetic spoken and written pseudowords > baseline and (B) logographic spoken and written pseudowords > baseline. Results are thresholded at *p* < .001 voxel-wise uncorrected and *p* < .05 FWE cluster corrected. Statistical maps are projected onto both segmented and inflated template brain anatomies.

similar left lateralised inferior frontal regions with the absence of right inferior frontal gyrus (opercularis); left inferior frontal gyrus (triangularis), insula, and precentral gyrus, right cerebellum, and bilateral supplementary motor area (see Figure 5.5B). Thus, speech-print convergence was found within a sub-set of regions identified previously by the literature (i.e., left inferior frontal gyrus (triangularis), precentral gyrus, and insula; Rueckl et al., 2015; Chyl et al., 2019) as a common signature for reading proficiency, irrespective of the orthographic structure of the writing system. These analyses support our hypothesis that alphabetic and logographic writing systems would exhibit convergent neural activity for spoken and written words in similar regions. Nevertheless, spelling-sound convergence was only observed in left inferior frontal regions, not middle to superior temporal gyri or inferior parietal lobule.

Overall summary of univariate analysis

Due to the systematic nature of alphabetic writing systems, we predicted that spoken language processing would be impacted via phonological restructuring or orthographic co-activation (Smith et al., 2021) and sub-word spelling-sound information would be favoured during reading, strengthening O-P mappings, and increasing reliance on the dorsal pathway. As logographic writing systems feature more arbitrary, holistic mappings between spelling and sound, we predicted that spoken language would not be impacted by literacy acquisition and that O-S mappings would be favoured during reading, increasing reliance on the ventral pathway. Overall, we found no evidence of orthographic effects on spoken language processing. However, univariate analyses supported our hypothesis that orthographic transparency will impact on written language processing, revealing that striking differences in the division of labour can arise solely due to the statistical structure of a writing system. Crucially, these univariate analyses are consistent with our behavioural results which similarly revealed differences in the division of labour between phonological and semantic processes; the alphabetic writing system capitalised on O-P mappings during reading acquisition, the logographic system favoured O-S mappings, and the orthographic transparency of the writing system did not impact on spoken language processing.

As predicted, regions associated with phonological and semantic processing were active for alphabetic and logographic spoken words. However, no evidence of phonological restructuring or online orthographic co-activation was observed for the alphabetic writing system; no regions associated with orthographic processing were active for alphabetic spoken words, nor were regions associated with phonological and orthographic processing more active for alphabetic than logographic spoken words.

While the dorsal reading pathway was active for both writing systems, these regions elicited greater neural activity for alphabetic than logographic written words. In contrast, whole-brain analyses revealed posterior regions along the ventral pathway were more active for logographic than alphabetic written words. ROI analysis supported these findings by evidencing a shift from greater neural activation for alphabetic > logographic written words in the most posterior ROIs along the ventral pathway to logographic > alphabetic in the most anterior ROI. Thus, our findings indicate that participant utilised the reading network in different ways to the learn the artificial writing systems and are consistent with Taylor et al. (2019) and Vinckier et al's (2007) description of a processing hierarchy along posterior to anterior vOT. Finally, while univariate analyses revealed that the orthographic transparency of the writing system can impact on reading acquisition and written language processing, conjunction analyses revealed convergent activity for spoken and written words from both systems within a sub-set of regions identified by Rueckl et al. (2015) and Chyl et al. (2019). Thus, our hypothesis that alphabetic and logographic writing systems would exhibit spelling-sound convergence in similar brain regions was supported.

5.2. Representational Similarity Analysis

Representational Similarity Analysis (RSA) enabled us to further our investigation beyond levels of neural activation by understanding how the nature of the writing system impacts on the underlying representations. We implemented this multivariate approach to decode the informational content of different brain regions by making conclusions about processing based on neural sensitivity to word similarity (Kriegeskorte et al., 2008). Thus, we used RSA to address our predictions about whether and how the orthographic transparency of a writing system impacts on neural sensitivity to phonemic, orthographic, and semantic similarity of alphabetic and logographic words. Finally, we conducted ROI analyses on first-level RSA correlation maps to maximise sensitivity and specificity and ensure that differences between writing systems were fully captured. 'Representational Similarity Analysis' within chapter 4 provides a comprehensive explanation of how RSA was conducted.

Auditory semantic monitoring

Phonemic and orthographic similarity

We first determined whether the systematicity of O-P mappings influenced the extent to which neural representations encode phonemic structure during listening. First, we predicted that neural response patterns will be sensitive to the phonemic similarity of pseudowords from both alphabetic and logographic writing systems. Phonemic dissimilarity matrices were computed as 1 minus the proportion of shared sounds between word pairs from within the same phonology. Note that for the alphabetic writing system this is equivalent to an orthographic dissimilarity matrix computed as

1 minus the proportion of shared symbols between word pairs, since there was a systematic, one-to-one mapping between sounds and symbols. To evaluate our hypotheses and identify regions that encoded phonemic structure for both writing systems and separately for the alphabetic and logographic system, we compared first-level RSA correlation maps representing neural sensitivity to phonemic structure for all spoken items, alphabetic spoken items, and logographic spoken items to zero using one-sample t-tests. Results are presented in Figure 5.6. Slices and peak coordinates associated with all results within this section are available on the OSF site.

Neural response patterns in bilateral frontal and temporal regions and left lateralised parietal and occipital regions encoded the phonemic structure of spoken items across both trained writing systems (see Figure 5.6A). These brain regions included left inferior frontal gyrus (triangularis and opercularis), superior and middle temporal gyri, supramarginal gyrus, precentral and postcentral gyri, and right calcarine sulcus. For the alphabetic writing system, representations were sensitive to the phonemic/ orthographic structure of alphabetic spoken items in fewer frontal, parietal, and temporal areas (alphabetic > 0; see Figure 5.6B). These regions included left rolandic operculum, right superior frontal gyrus, transverse temporal gyrus, anterior cingulate

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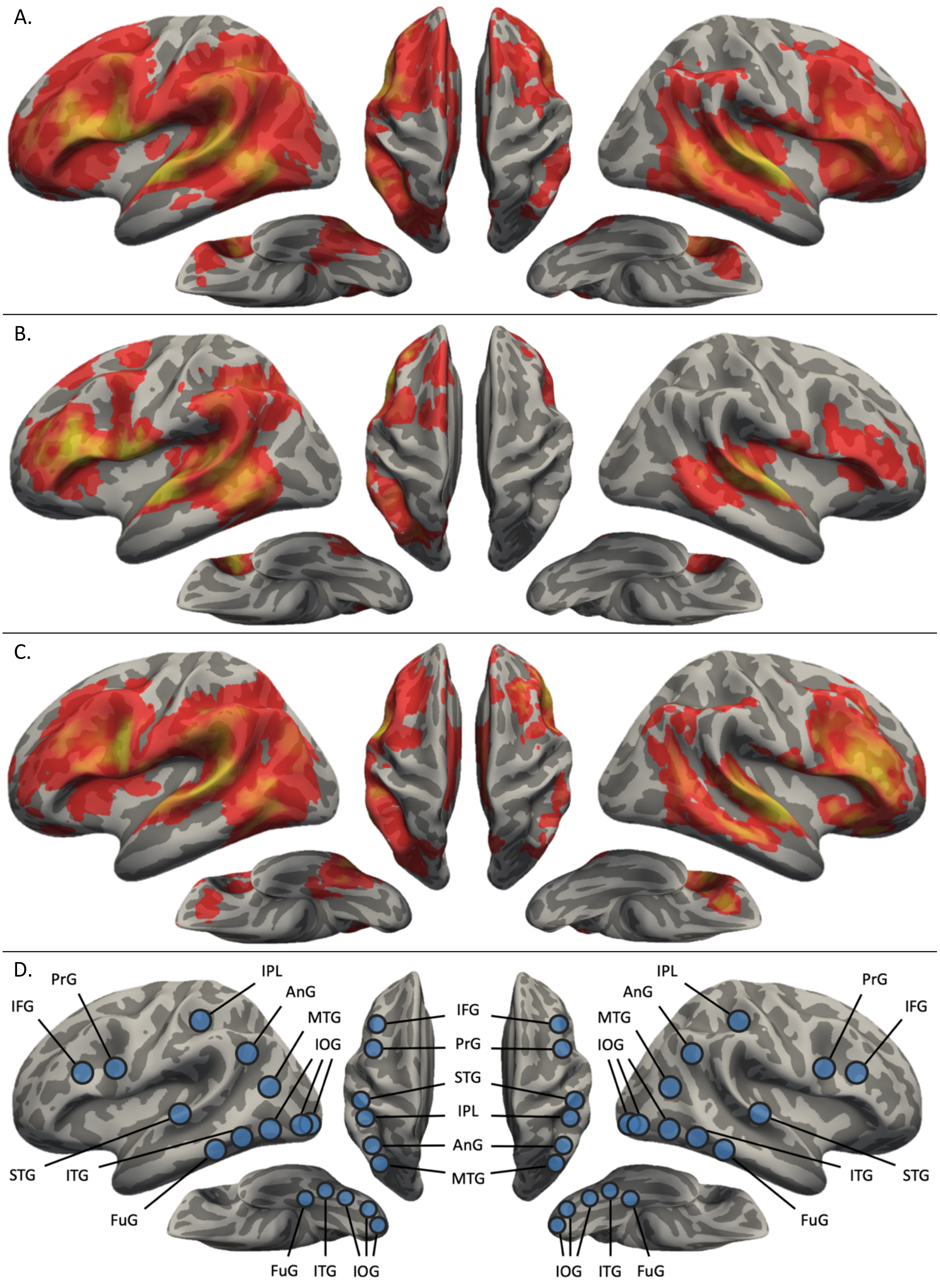
Figure 5.6. Brain regions where neural representations were sensitive to the phonemic similarity of (A) all spoken pseudowords > 0, (B) alphabetic spoken pseudowords > 0, and (C) logographic spoken pseudowords > 0. RSA results are TFCE enhanced using permutation testing and thresholded at voxel-wise FWE corrected $p < .05$. (D) Locations of ROIs used to perform ROI analyses on RSA maps. No ROIs were more sensitive to the phonemic similarity of alphabetic > logographic spoken pseudowords ($p < .05$ without Bonferroni correction). IFG, inferior frontal gyrus; PrG, precentral gyrus; IPL, inferior parietal lobule; AnG, angular gyrus; MTG, middle temporal gyrus; IOG, inferior occipital gyrus; FuG, fusiform gyrus; ITG, inferior temporal gyrus; STG, superior temporal gyrus. Statistical maps and ROIs are projected onto segmented and inflated template brain anatomies.



cortex, insula, and precentral gyrus, and bilateral middle and inferior frontal gyri, and superior and middle temporal gyri. For the logographic writing system, neural activation patterns captured the phonemic structure logographic spoken items in additional bilateral frontal regions and left parietal and occipital areas (logographic >

0; see Figure 5.6C). These regions included left inferior frontal gyrus (triangularis and opercularis), superior, middle and inferior temporal gyri, inferior parietal lobule, supramarginal gyrus, inferior occipital cortex, medial orbitofrontal cortex, right precuneus, and bilateral precentral gyri. Combined, these analyses support our experimental hypothesis as they indicate that neural representations in bilateral frontal and temporal regions and left lateralised parietal areas reflect information about the phonological form of both alphabetic and logographic spoken words.

Due to a systematic mapping between sounds and symbols, we predicted that regions associated with spoken language and orthographic processing would be more sensitive to the phonemic similarity of alphabetic > logographic spoken pseudowords. No brain regions were expected to exhibit greater sensitivity to the phonemic structure of logographic > alphabetic items. To evaluate these hypotheses, we compared first-level RSA correlation maps representing neural sensitivity to the phonemic structure of alphabetic and logographic spoken pseudowords using voxel-wise paired-samples t-tests. In addition, we performed ROI analyses on first-level correlation maps in brain regions associated with visual, spoken language and semantic processing, and spelling-sound conversion before conducting paired-samples t-tests using an alphabetic > logographic contrast (see ‘Region of Interest (ROI) analysis’ on page 126 of chapter 4 for more information). Figure 5.6D displays the approximate location of our ROIs and whether neural representations were significantly more sensitive to the phonemic similarity of alphabetic or logographic spoken pseudowords. Results are presented in Figure 5.7 and Table 5.2 provide additional details including anatomical labels, coordinates, and associated statistics. Combined, these analyses revealed no significant differences in neural sensitivity to phonemic similarity between the two

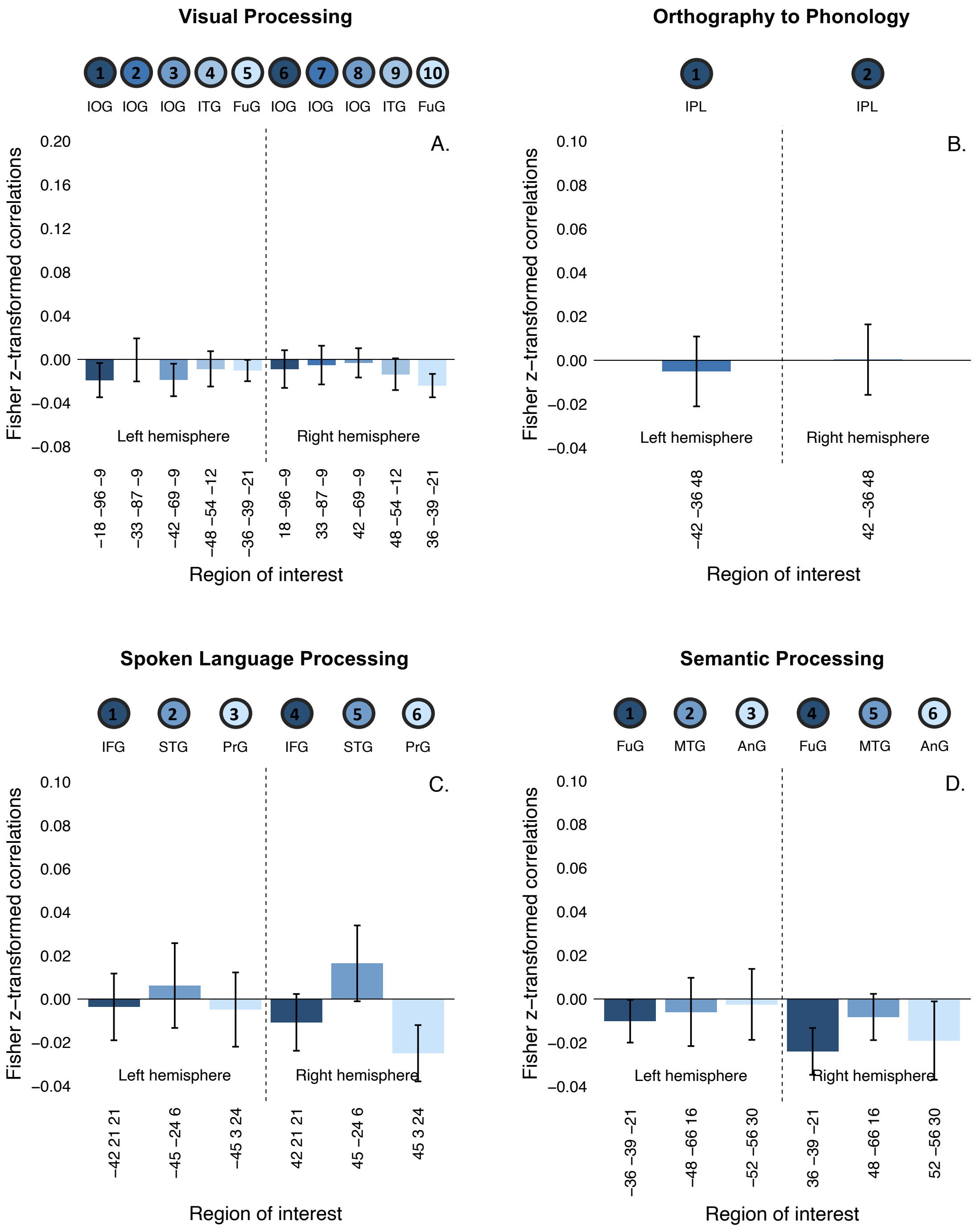


Figure 5.7. Group-level RSA Correlations Associated with Paired-Samples t-tests Comparing Neural Sensitivity to the Phonemic Similarity of Alphabetic > Logographic Spoken Pseudowords within ROIs

Note. First-level RSA correlations were averaged within each ROI for each writing system before performing paired-samples t-tests using an alphabetic > logographic contrast. Error bars denote within-subjects SE. *p*-values are not Bonferroni corrected; <.001 = ***, <.01 = **, <.05 = *. Abbreviated anatomical labels correspond to Figure 5.6D; coloured discs correspond to Table 5.2A-D and Figures 4.5-4.8 and Tables 4.2-4.5 (see chapter 4). IFG, inferior frontal gyrus; PrG, precentral gyrus; IPL, inferior parietal lobule; AnG, angular gyrus; MTG, middle temporal gyrus; IOG, inferior occipital gyrus; FuG, fusiform gyrus; ITG, inferior temporal gyrus; STG, superior temporal gyrus.

Table 5.2. *Location, Size, and Statistics Associated with ROI Analyses of RSA Maps Comparing Neural Sensitivity to the Phonemic Similarity of Alphabetic > Logographic Spoken Pseudowords*

Location (AAL)	Hemisphere	Size (mm)	X	Y	Z	*β*	*t*	*p*	Key
A. Inferior Occipital Cortex	Left	8	-18	-96	-9	-.02	-1.21	.881	①
Inferior Occipital Cortex	Left	8	-33	-87	-9	.00	-.02	.509	②
Inferior Occipital Cortex	Left	8	-42	-69	-9	-.02	-1.26	.891	③
Inferior Temporal Gyrus	Left	8	-48	-54	-12	-.01	-.54	.701	④
Fusiform Gyrus	Left	8	-36	-39	-21	-.01	-1.04	.845	⑤
Inferior Occipital Cortex	Right	8	18	-96	-9	-.01	-.51	.694	⑥
Inferior Occipital Cortex	Right	8	33	-87	-9	-.01	-.29	.614	⑦
Inferior Occipital Cortex	Right	8	42	-69	-9	.00	-.24	.593	⑧
Inferior Temporal Gyrus	Right	8	48	-54	-12	-.01	-.93	.820	⑨
Fusiform Gyrus	Right	8	36	-39	-21	-.02	-2.24	.983	⑩
B. Inferior Parietal Lobule	Left	8	-42	-36	48	-.01	-.32	.623	①
Inferior Parietal Lobule	Right	8	42	-36	48	.00	.02	.492	②
C. Inferior Frontal Gyrus	Left	8	-42	21	21	.00	-.24	.592	①
Superior Temporal Gyrus	Left	8	-45	-24	6	.01	.32	.376	②
Precentral Gyrus	Left	8	-45	3	24	.00	-.28	.610	③
Inferior Frontal Gyrus	Right	8	42	21	21	-.01	-.82	.790	④
Superior Temporal Gyrus	Right	8	45	-24	6	.02	.94	.178	⑤
Precentral Gyrus	Right	8	45	3	24	-.02	-1.92	.967	⑥
D. Fusiform Gyrus	Left	8	-36	-39	-21	-.01	-1.04	.845	①
Middle Temporal Gyrus	Left	8	-48	-66	16	-.01	-.38	.646	②
Angular Gyrus	Left	8	-52	-56	30	.00	-.15	.560	③
Fusiform Gyrus	Right	8	36	-39	-21	-.02	-2.24	.983	④
Middle Temporal Gyrus	Right	8	48	-66	16	-.01	-.78	.778	⑤
Angular Gyrus	Right	8	52	-56	30	-.02	-1.06	.850	⑥

Note. Location, size, and statistics associated with visual processing (A), IPL (B; orthography to phonology conversion), spoken language processing (C), and semantic processing (D) ROIs. AAL refers to Automated Anatomical Labelling. *β* represents the group-level RSA correlation associated with each paired-samples *t*-test implementing the contrast alphabetic > logographic. *p*-values are not Bonferroni corrected. Key colours and numbers correspond to the coloured bars and discs within Figure 5.7A-D and the coloured discs within Figures 4.5-4.8 and Tables 4.2-4.5 (see chapter 4).

artificial writing systems in any regions. Thus, whilst many brain regions encoded the phonemic structure of the newly learned words, the extent to which this was the case was not modulated by the orthographic transparency of the writing system.

We aimed to determine whether the systematicity of O-P mappings influenced the extent to which neural representations encode orthographic structure during listening. We predicted that neural response patterns will only be sensitive to the orthographic similarity of pseudowords from the alphabetic writing system. No brain regions were expected to exhibit sensitivity to the orthographic structure of logographic spoken items. Orthographic dissimilarity matrices were computed as 1 minus the proportion of shared symbols between word pairs from within the same orthography. Note that for the alphabetic writing system this is equivalent to a phonemic dissimilarity matrix computed as 1 minus the proportion of shared sounds between word pairs, since there was a systematic, one-to-one mapping between symbols and sounds. To evaluate our hypotheses and identify brain regions that encoded orthographic structure for both writing systems and separately for the alphabetic and logographic writing system, we compared first-level correlation maps representing neural sensitivity to orthographic structure for all spoken items, alphabetic spoken items, and logographic spoken words to zero using one-sample t-tests. Results are presented in Figure 5.8.

No brain regions encoded orthographic structure across both the alphabetic and logographic writing system. As the orthographic dissimilarity matrix was equivalent to a phonemic dissimilarity matrix for the alphabetic system, alphabetic > 0 produced the same results as those in Figure 5.6B (see page 151). Thus, representations were sensitive to the phonemic/orthographic structure of alphabetic spoken words in

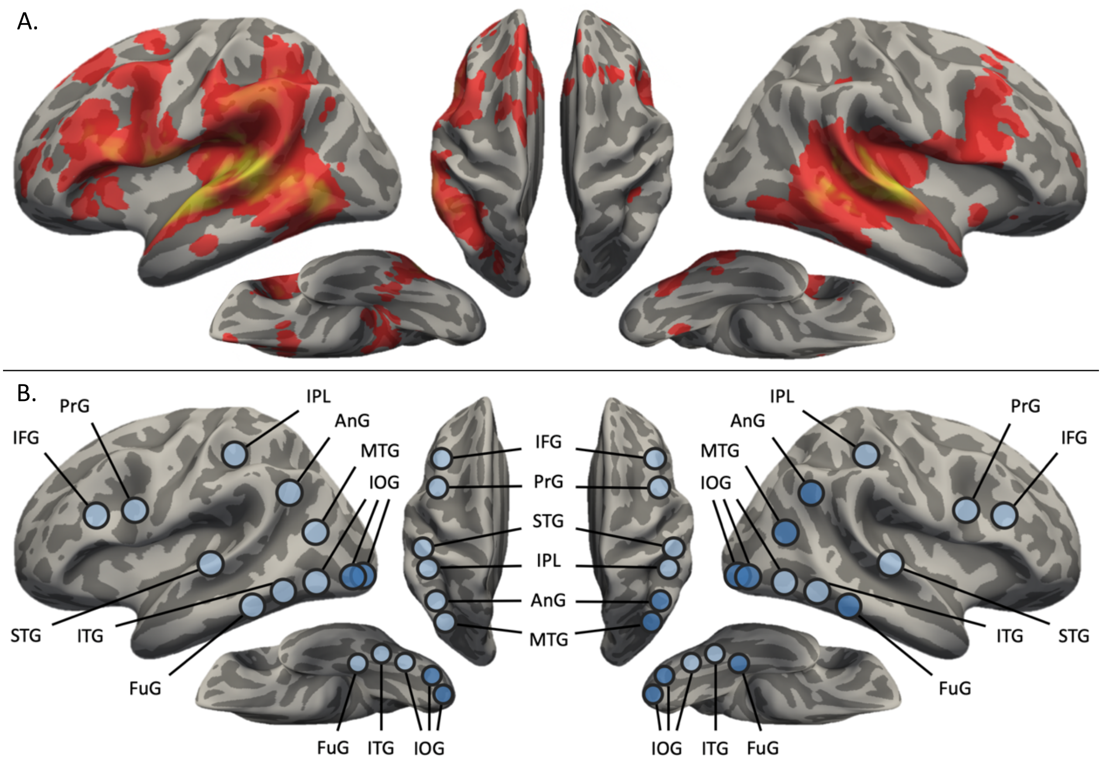


Figure 5.8. Brain regions where neural representations were more sensitive to the orthographic similarity of alphabetic > logographic spoken pseudowords (A). RSA results are TFCE enhanced using permutation testing and thresholded at voxel-wise FWE corrected $p < .05$. (B) Locations of ROIs used to perform ROI analyses on RSA maps. Light blue represents ROIs exhibiting greater sensitivity to the orthographic similarity of alphabetic > logographic spoken pseudowords; dark blue indicates no difference in sensitivity to the orthographic similarity of alphabetic > logographic spoken pseudowords ($p < .05$ without Bonferroni correction). IFG, inferior frontal gyrus; PrG, precentral gyrus; IPL, inferior parietal lobule; AnG, angular gyrus; MTG, middle temporal gyrus; IOG, inferior occipital gyrus; FuG, fusiform gyrus; ITG, inferior temporal gyrus; STG, superior temporal gyrus. Statistical maps and ROIs are projected onto segmented and inflated template brain anatomies.

bilateral frontal and temporal areas and left lateralised parietal regions including left rolandic operculum, right superior frontal gyrus, transverse temporal gyrus, anterior cingulate cortex, insula, and precentral gyrus, and bilateral middle and inferior frontal gyri, and superior and middle temporal gyri. In contrast, Logographic > 0 revealed no regions that captured the orthographic structure of logographic spoken words.

Due to a systematic mapping between sounds and symbols, we predicted that regions associated with spoken language and orthographic processing would be more sensitive to the orthographic similarity of alphabetic > logographic spoken pseudowords. No regions were expected to exhibit greater sensitivity to the orthographic structure of logographic > alphabetic items. To evaluate these hypotheses, we compared first-level RSA correlation maps representing neural sensitivity to the orthographic structure of alphabetic and logographic spoken pseudowords using voxel-wise paired-samples t-tests. Neural representations were more sensitive to the orthographic structure of alphabetic spoken items in bilateral frontal and temporal areas and left lateralised parietal regions (alphabetic > logographic; see Figure 5.8A). These regions included left supramarginal gyrus, medial orbitofrontal cortex, caudate nucleus, and postcentral gyrus, right angular gyrus and insula, and bilateral superior and inferior frontal gyri (triangularis and opercularis), superior, middle and inferior temporal gyri, superior temporal pole, transverse temporal gyri, and rolandic operculum. In contrast, logographic > alphabetic revealed that no brain regions captured significantly more information about the orthographic similarity of logographic spoken items.

In addition, we performed ROI analyses on first-level correlation maps in regions associated with visual, spoken language and semantic processing, and spelling-sound conversion before conducting paired-samples t-tests using an alphabetic > logographic contrast. Figure 5.8B displays the approximate location of our ROIs and whether neural representations were significantly more sensitive to the orthographic similarity of alphabetic or logographic spoken pseudowords. Results are presented in Figure 5.9 and Table 5.3 provide additional details including anatomical labels, coordinates, and associated statistics. Representations were more sensitive to the orthographic structure

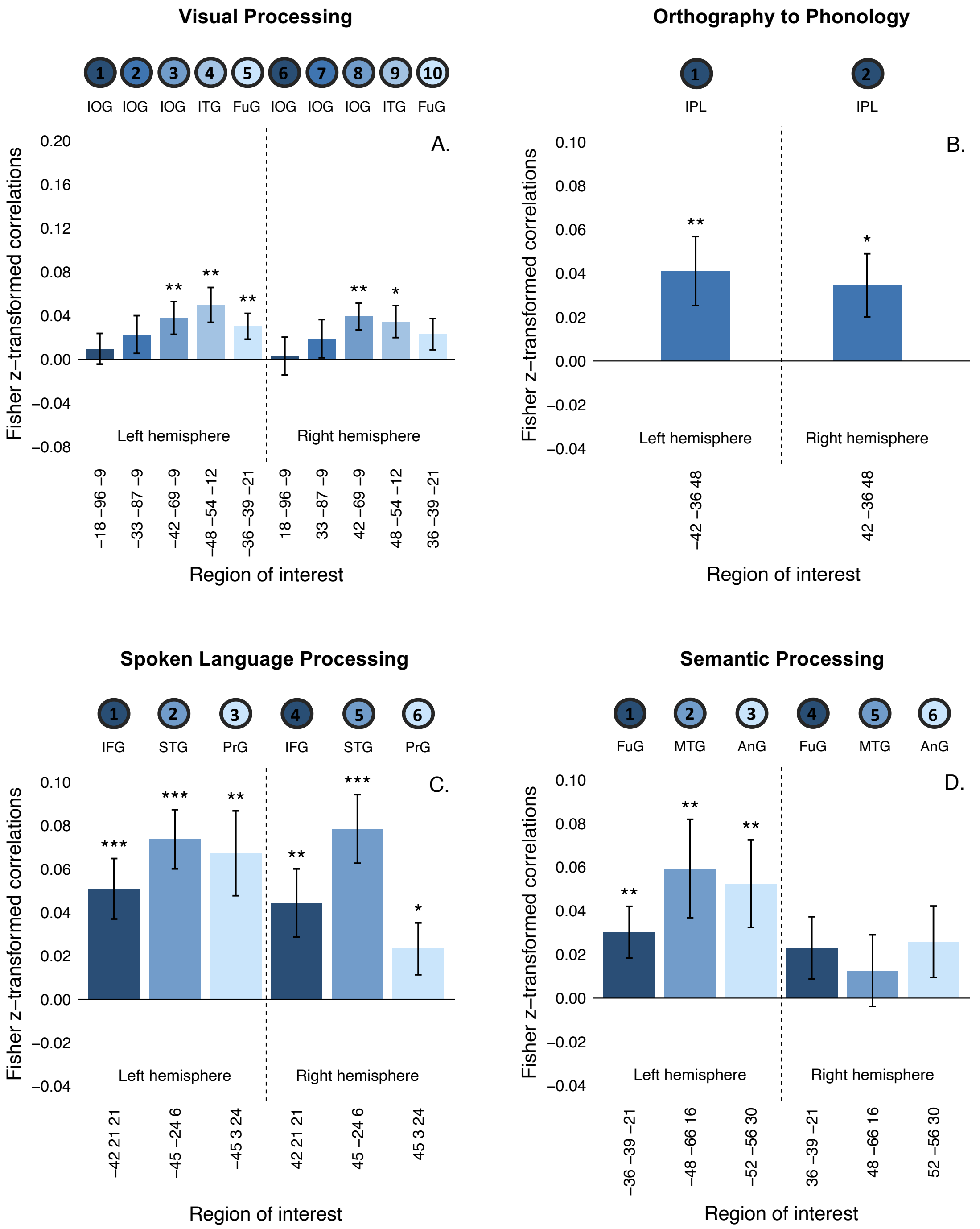


Figure 5.9. RSA Correlations Associated with Paired-Samples t-tests Comparing Neural Sensitivity to the Orthographic Similarity of Alphabetic > Logographic Spoken Pseudowords within ROIs

Note. First-level RSA correlations were averaged within each ROI for each writing system before performing paired-samples t-tests using an alphabetic > logographic contrast. Error bars denote within-subjects SE. *p*-values are not Bonferroni corrected; <.001 = ***, <.01 = **, <.05 = *. Abbreviated anatomical labels correspond to Figure 5.8B; coloured discs correspond to Table 5.3A-D and Figures 4.5-4.8 and Tables 4.2-4.5 (see chapter 4). IFG, inferior frontal gyrus; PrG, precentral gyrus; IPL, inferior parietal lobule; AnG, angular gyrus; MTG, middle temporal gyrus; IOG, inferior occipital gyrus; FuG, fusiform gyrus; ITG, inferior temporal gyrus; STG, superior temporal gyrus.

Table 5.3. *Location, Size, and Statistics Associated with ROI Analyses of RSA Maps Comparing Neural Sensitivity to the Orthographic Similarity of Alphabetic > Logographic Spoken Pseudowords*

Location (AAL)	Hemisphere	Size (mm)	X	Y	Z	β	*t*	*p*	Key
A. Inferior Occipital Cortex	Left	8	-18	-96	-9	.01	.68	.250	1
Inferior Occipital Cortex	Left	8	-33	-87	-9	.02	1.31	.101	2
Inferior Occipital Cortex	Left	8	-42	-69	-9	.04	2.52	.010	3
Inferior Temporal Gyrus	Left	8	-48	-54	-12	.05	3.12	.002	4
Fusiform Gyrus	Left	8	-36	-39	-21	.03	2.55	.009	5
Inferior Occipital Cortex	Right	8	18	-96	-9	.00	.17	.434	6
Inferior Occipital Cortex	Right	8	33	-87	-9	.02	1.08	.146	7
Inferior Occipital Cortex	Right	8	42	-69	-9	.04	3.24	.002	8
Inferior Temporal Gyrus	Right	8	48	-54	-12	.03	2.35	.014	9
Fusiform Gyrus	Right	8	36	-39	-21	.02	1.61	.060	10
B. Inferior Parietal Lobule	Left	8	-42	-36	48	.04	2.61	.008	1
Inferior Parietal Lobule	Right	8	42	-36	48	.03	2.40	.013	2
C. Inferior Frontal Gyrus	Left	8	-42	21	21	.05	3.66	.001	1
Superior Temporal Gyrus	Left	8	-45	-24	6	.07	5.40	<.001	2
Precentral Gyrus	Left	8	-45	3	24	.07	3.44	.001	3
Inferior Frontal Gyrus	Right	8	42	21	21	.04	2.83	.005	4
Superior Temporal Gyrus	Right	8	45	-24	6	.08	4.96	<.001	5
Precentral Gyrus	Right	8	45	3	24	.02	1.95	.032	6
D. Fusiform Gyrus	Left	8	-36	-39	-21	.03	2.55	.009	1
Middle Temporal Gyrus	Left	8	-48	-66	16	.06	2.64	.007	2
Angular Gyrus	Left	8	-52	-56	30	.05	2.61	.008	3
Fusiform Gyrus	Right	8	36	-39	-21	.02	1.61	.060	4
Middle Temporal Gyrus	Right	8	48	-66	16	.01	.77	.225	5
Angular Gyrus	Right	8	52	-56	30	.03	1.58	.064	6

Note. Location, size, and statistics associated with visual processing (A), IPL (B; orthography to phonology conversion), spoken language processing (C), and semantic processing (D) ROIs. AAL refers to Automated Anatomical Labelling. β represents the group-level RSA correlation associated with each paired-samples *t*-test implementing the contrast alphabetic > logographic. *p*-values are not Bonferroni corrected. Key colours and numbers correspond to the coloured bars and discs within Figure 5.9A-D and the coloured discs within Figures 4.5-4.8 and Tables 4.2-4.5 (see chapter 4).

of alphabetic spoken items in left fusiform, middle temporal and angular gyri, and bilateral anterior inferior occipital cortex, inferior temporal gyri, inferior parietal lobule, and inferior frontal, superior temporal, and precentral gyri. No ROIs captured more information about the orthographic similarity of logographic spoken items.

Overall, these analyses revealed that the extent to which neural representations encode the orthographic structure of newly learned words during listening is modulated by the orthographic transparency of the writing system. Representations were more sensitive to the orthographic structure of alphabetic spoken items in bilateral frontal, temporal and parietal regions, including middle to anterior vOT (see Figures 5.8A and 5.8B). These regions have been associated with auditory processing, phonological non-lexical and lexical representations, phonological representations of word pronunciation, and semantic processing (i.e. left superior and inferior frontal gyri, medial orbitofrontal cortex, precentral gyrus, inferior parietal lobule, supramarginal gyrus, middle and inferior temporal gyri, fusiform and angular gyri, bilateral superior and transverse temporal gyri and superior temporal poles; Davis & Gaskell, 2009; Binder et al., 2009; Fischer-Baum et al., 2018). In addition, representations captured more orthographic information about alphabetic spoken items in regions associated with orthographic processing and spelling-sound and spelling-meaning conversion (i.e. left fusiform, inferior temporal gyrus, and inferior parietal lobule, bilateral inferior occipital cortex; Taylor et al., 2013; Fiebach et al., 2002; Taylor et al., 2014; Purcell et al., 2014). No regions captured orthographic similarity in spoken items in the logographic system. Thus, these findings support our hypotheses as the systematicity of O-P mappings influenced whether representations encoded orthographic structure during listening. Brain regions only encoded the orthographic structure of newly learned spoken words associated with the transparent alphabetic writing system.

Alphabetic writing systems are characterised by a systematic, one-to-one mapping between phonemes and graphemes. This relationship between sounds and symbols prevents us from deconfounding neural sensitivity to phonemic and orthographic similarity. We therefore aimed to determine whether the systematicity of O-P mappings influenced the extent to which representations encode both phonemic and orthographic structure during listening. We hypothesised that neural response patterns will be sensitive to the phonemic and orthographic similarity of both alphabetic and logographic spoken words. However, an arbitrary, holistic relationship between sounds and spellings requires us to investigate neural sensitivity to phonemic and orthographic structure independently for the logographic writing system.

First-level RSA correlation maps representing neural sensitivity to phonemic and orthographic similarity were combined for the logographic writing system to create an equivalent to results from the alphabetic system. For each participant, correlations between their neural RDM and phonemic and orthographic dissimilarity matrices were added together at each voxel to generate a combined representation of sensitivity to phonemic and orthographic similarity. To evaluate our hypotheses and identify regions that encoded the phonemic/orthographic structure of spoken items from different writing systems, we compared first-level RSA correlation maps to zero using one-sample t-tests. First, we conducted these analyses using correlation maps representing sensitivity to phonemic/orthographic structure for alphabetic spoken words. Next, equivalent analyses were conducted using our combined first-level correlation maps representing sensitivity to phonemic and orthographic structure for logographic spoken words. Results are presented in Figure 5.10. As the first predicted RDM estimated phonemic/orthographic dissimilarity for the alphabetic system, alphabetic > 0 produced the same results as those in Figure 5.6B (see page 151). Neural response patterns captured the phonemic/ orthographic structure of logographic spoken words in fewer left-lateralised frontal and temporal regions and a small cluster located in the left middle occipital lobe (logographic > 0; see Figure 5.10A). These regions included left middle and inferior frontal (triangularis) gyri, superior and middle temporal gyri, middle occipital gyrus, rolandic operculum, and precentral gyrus. Combined, these analyses support our hypothesis as neural representations reflect information about the phonemic and orthographic form of alphabetic and logographic words.

Exclusionary masking

Neural sensitivity to phonemic and orthographic similarity appears to be wider spread for the alphabetic than the logographic writing system. We decided to explore these

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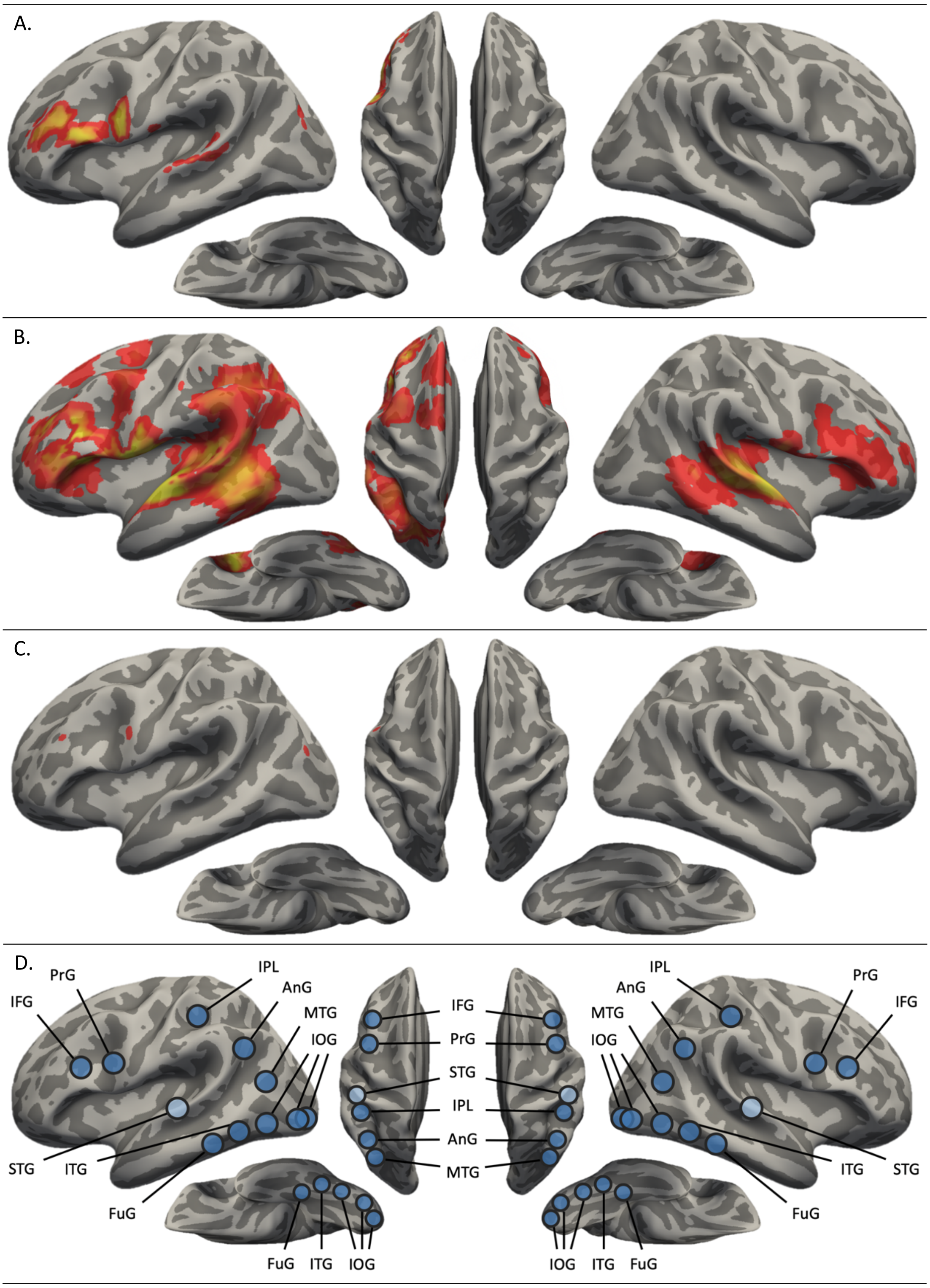
Figure 5.10. Brain regions where representations were (A) sensitive to the phonemic or orthographic similarity of logographic spoken pseudowords > 0, (B) sensitive to the phonemic or orthographic similarity of alphabetic but not logographic spoken pseudowords > 0, and (C) sensitive to the phonemic or orthographic structure of logographic but not alphabetic spoken pseudowords > 0. RSA results are TFCE enhanced using permutation testing and thresholded at voxel-wise FWE corrected $p < .05$. (D) Locations of ROIs used to perform analyses on RSA maps. Light blue represents ROIs exhibiting greater neural sensitivity to the phonemic or orthographic similarity of alphabetic than logographic spoken pseudowords; dark blue represents ROIs with no differences in sensitivity to the phonemic or orthographic similarity of alphabetic and logographic spoken pseudowords (alphabetic > logographic; $p < .05$ without Bonferroni correction). IFG, inferior frontal gyrus; PrG, precentral gyrus; IPL, inferior parietal lobule; AnG, angular gyrus; MTG, middle temporal gyrus; IOG, inferior occipital gyrus; FuG, fusiform gyrus; ITG, inferior temporal gyrus; STG, superior temporal gyrus. Statistical maps and ROIs are projected onto segmented and inflated template brain anatomies.



differences further by isolating regions that only exhibited sensitivity for one trained writing system. Here, significant voxels within our group-level t-map representing neural sensitivity to the phonemic or orthographic structure of logographic spoken items were excluded from equivalent first-level correlation maps for the alphabetic system, and vice versa, before conducting one-sample t-tests. Alphabetic > 0 revealed that bilateral frontal and temporal areas and left lateralised parietal regions were only sensitive to the phonemic/orthographic structure of alphabetic spoken items. These regions included left rolandic operculum, right superior frontal gyrus, transverse temporal gyrus, precentral gyrus, and insula, and bilateral middle and inferior frontal (triangularis and opercularis) gyri, and superior and middle temporal gyri (see Figure 5.10B). Logographic > 0 revealed a small number of significant voxels located in left inferior frontal gyrus (triangularis and opercularis), middle frontal gyrus, superior temporal gyrus, middle occipital gyrus, rolandic operculum, and precentral gyrus (see Figure 5.10C). Combined, these analyses confirm that sensitivity to phonemic and orthographic structure is more widely spread for the alphabetic writing system.

Contrasting alphabetic and logographic writing systems

Due to a systematic mapping between sounds and symbols, we predicted that regions associated with spoken language and orthographic processing would be more sensitive to the phonemic and orthographic similarity of alphabetic > logographic spoken pseudowords. No brain regions were expected to exhibit greater sensitivity to the phonemic or orthographic structure of logographic > alphabetic words. To evaluate these hypotheses, we compared first-level RSA correlation maps representing neural sensitivity to the phonemic or orthographic structure of alphabetic and logographic spoken pseudowords using voxel-wise paired-samples t-tests. Note that no voxels were excluded from these maps. In addition, we performed equivalent ROI analyses to those described previously. Figure 5.10D displays the approximate location of our ROIs and whether neural representations were significantly more sensitive to the phonemic and orthographic similarity of trained alphabetic than logographic spoken words. Results are presented in Figure 5.11 and Table 5.4 provide additional information including anatomical labels, coordinates, and associated statistics.

Overall summary of phonemic and orthographic similarity

Combined, these analyses revealed that representations were more sensitive to the phonemic/orthographic structure of alphabetic > logographic spoken items in bilateral superior temporal gyrus only. Both regions have been associated with auditory processing, while left superior temporal gyrus has also been linked to non-lexical phonological processing (Davis & Gaskell, 2009). Thus, these results do not support our hypothesis as no brain regions associated with orthographic processing exhibited greater sensitivity to the phonemic and orthographic structure of alphabetic > logographic items. As predicted, no regions were more sensitive to the phonemic or orthographic structure of logographic > alphabetic items. Overall, we found that whilst many regions encoded the phonemic and orthographic structure of the newly learned words, the extent to which this was the case was only modulated by the orthographic transparency of the writing system in bilateral superior temporal gyrus. Thus, the statistical structure of the writing system does appear to impact on neural sensitivity to the phonemic or orthographic structure of alphabetic spoken pseudowords.

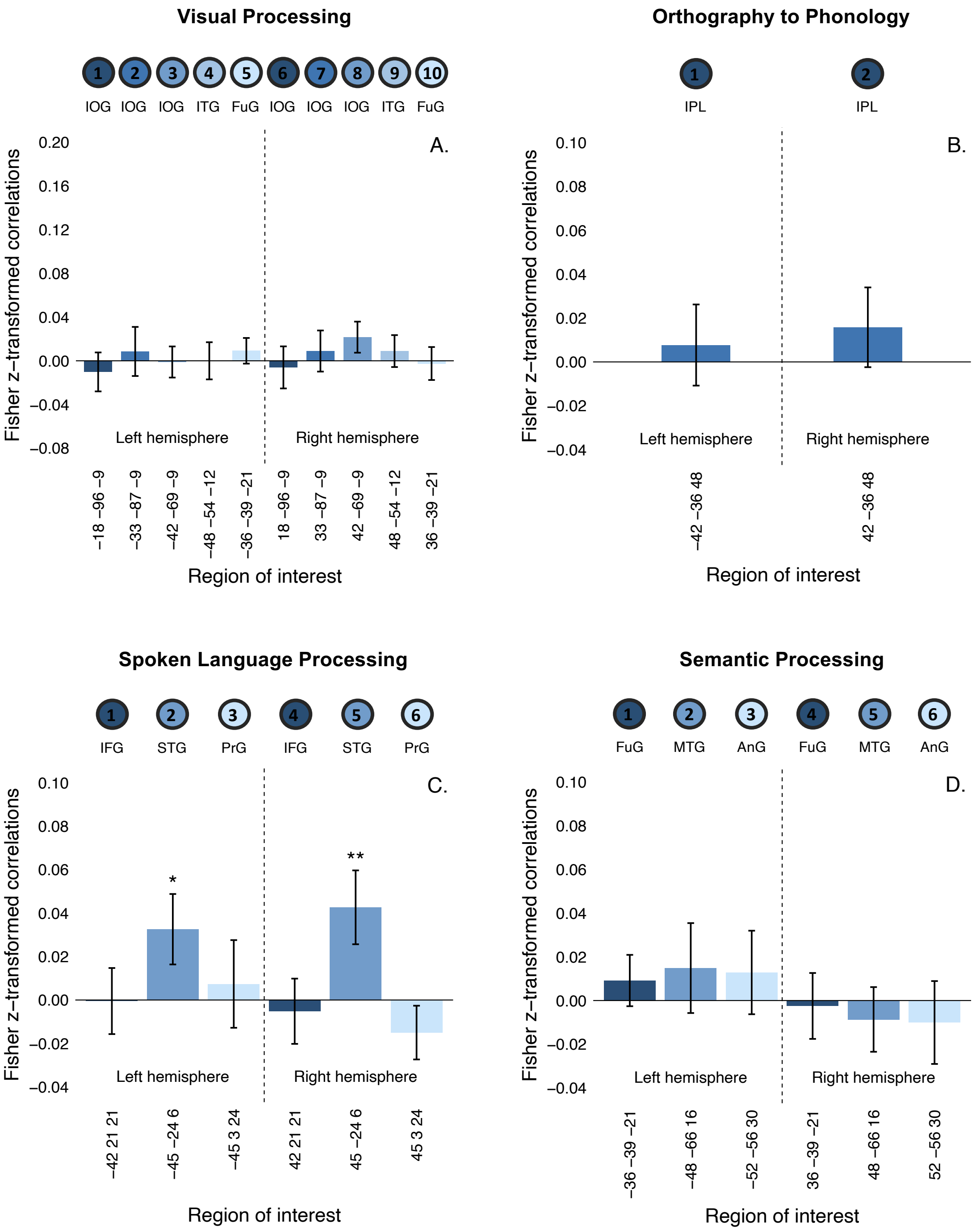


Figure 5.11. RSA Correlations Associated with Paired-Samples t-tests Comparing Sensitivity to the Phonemic/Orthographic Similarity of Alphabetic > Logographic Spoken Pseudowords within ROIs

Note. First-level RSA correlations were averaged within each ROI for each writing system before performing paired-samples t-tests using an alphabetic > logographic contrast. Error bars denote within-subjects SE. *p*-values are not Bonferroni corrected; <.001 = ***, <.01 = **, <.05 = *. Abbreviated anatomical labels correspond to Figure 5.10D; coloured discs correspond to Table 5.4A-D and Figures 4.5-4.8 and Tables 4.2-4.5 (see chapter 4). IFG, inferior frontal gyrus; PrG, precentral gyrus; IPL, inferior parietal lobule; AnG, angular gyrus; MTG, middle temporal gyrus; IOG, inferior occipital gyrus; FuG, fusiform gyrus; ITG, inferior temporal gyrus; STG, superior temporal gyrus.

Table 5.4. *Statistics Associated with ROI Analyses of RSA Maps Comparing Neural Sensitivity to the Phonemic/Orthographic Similarity of Alphabetic > Logographic Spoken Pseudowords*

Location (AAL)	Hemisphere	Size (mm)	X	Y	Z	β	*t*	*p*	Key
A. Inferior Occipital Cortex	Left	8	-18	-96	-9	-.01	-.57	.713	1
Inferior Occipital Cortex	Left	8	-33	-87	-9	.01	.38	.353	2
Inferior Occipital Cortex	Left	8	-42	-69	-9	.00	-.08	.530	3
Inferior Temporal Gyrus	Left	8	-48	-54	-12	.00	.00	.500	4
Fusiform Gyrus	Left	8	-36	-39	-21	.01	.78	.222	5
Inferior Occipital Cortex	Right	8	18	-96	-9	-.01	-.31	.622	6
Inferior Occipital Cortex	Right	8	33	-87	-9	.01	.48	.319	7
Inferior Occipital Cortex	Right	8	42	-69	-9	.02	1.52	.071	8
Inferior Temporal Gyrus	Right	8	48	-54	-12	.01	.61	.274	9
Fusiform Gyrus	Right	8	36	-39	-21	.00	-.16	.564	10
B. Inferior Parietal Lobule	Left	8	-42	-36	48	.01	.42	.341	1
Inferior Parietal Lobule	Right	8	42	-36	48	.02	.87	.197	2
C. Inferior Frontal Gyrus	Left	8	-42	21	21	.00	-.03	.512	1
Superior Temporal Gyrus	Left	8	-45	-24	6	.03	2.01	.028	2
Precentral Gyrus	Left	8	-45	3	24	.01	.37	.359	3
Inferior Frontal Gyrus	Right	8	42	21	21	-.01	-.34	.633	4
Superior Temporal Gyrus	Right	8	45	-24	6	.04	2.51	.010	5
Precentral Gyrus	Right	8	45	3	24	-.01	-1.21	.881	6
D. Fusiform Gyrus	Left	8	-36	-39	-21	.01	.78	.222	1
Middle Temporal Gyrus	Left	8	-48	-66	16	.01	.72	.239	2
Angular Gyrus	Left	8	-52	-56	30	.01	.67	.254	3
Fusiform Gyrus	Right	8	36	-39	-21	.00	-.16	.564	4
Middle Temporal Gyrus	Right	8	48	-66	16	-.01	-.58	.718	5
Angular Gyrus	Right	8	52	-56	30	-.01	-.53	.699	6

Note. Location, size, and statistics associated with visual processing (A), IPL (B; orthography to phonology conversion), spoken language processing (C), and semantic processing (D) ROIs. AAL refers to Automated Anatomical Labelling. β represents the group-level RSA correlation associated with each paired-samples *t*-test implementing the contrast alphabetic > logographic. *p*-values are not Bonferroni corrected. Key colours and numbers correspond to the coloured bars and discs within Figure 5.11A-D and the coloured discs within Figures 4.5-4.8 and Tables 4.2-4.5 (see chapter 4).

Semantic similarity

We aimed to determine whether the systematicity of O-P mappings influenced the extent to which neural representations encode semantic structure during listening. First, we predicted that neural response patterns will be sensitive to the semantic similarity of alphabetic and logographic words. Semantic dissimilarity matrices represented whether the meanings of word pairs from within the same writing system were from the same semantic category (same category = 0, different categories = 1). To evaluate our hypotheses and identify regions that encoded semantic similarity for both writing systems and separately for the alphabetic and logographic system, we compared first-level correlation maps representing neural sensitivity to semantic similarity for all spoken items, alphabetic spoken items, and logographic spoken items to zero using one-sample t-tests. These analyses revealed that no regions captured information about the semantic similarity of alphabetic or logographic words.

Due to an arbitrary rather than systematic mapping between sounds and symbols, we predicted that regions associated with semantic processing would be more sensitive to the semantic similarity of logographic > alphabetic spoken pseudowords. No regions were expected to exhibit greater sensitivity to semantic structure for the alphabetic > logographic system. To evaluate these hypotheses, we compared first-level RSA correlation maps representing sensitivity to the semantic similarity of logographic and alphabetic spoken pseudowords using voxel-wise paired-samples t-tests. Results are presented in Figure 5.12A. Neural representations were more sensitive to the semantic structure of logographic words in bilateral parietal and occipital areas and left lateralised posterior temporal regions (logographic > alphabetic). These regions included left middle temporal gyrus, middle and posterior cingulate cortex, and

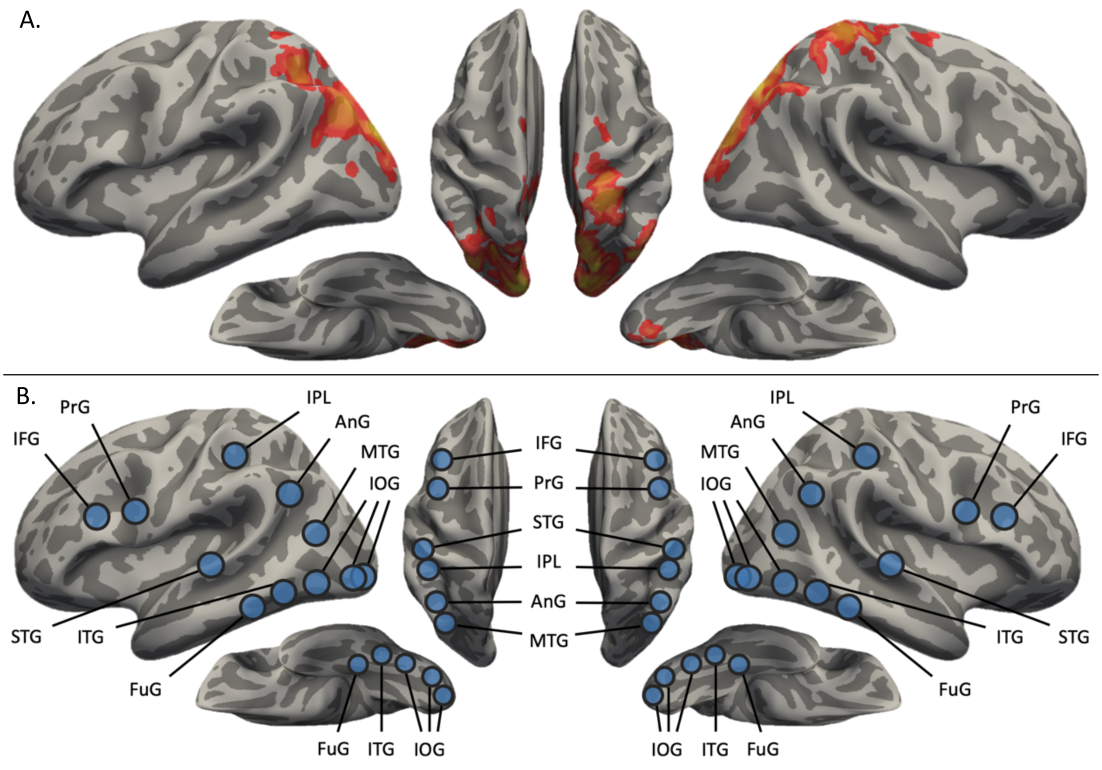


Figure 5.12. Brain regions where neural representations were more sensitive to the semantic similarity of logographic > alphabetic items when participants recalled the meaning of spoken pseudowords (A). RSA results are TFCE enhanced using permutation testing and thresholded at voxel-wise FWE corrected $p < .05$. (B) Locations of ROIs used to perform ROI analyses on RSA maps. No ROIs were more sensitive to the semantic similarity of logographic > alphabetic spoken pseudowords ($p < .05$ without Bonferroni correction). IFG, inferior frontal gyrus; PrG, precentral gyrus; IPL, inferior parietal lobule; AnG, angular gyrus; MTG, middle temporal gyrus; IOG, inferior occipital gyrus; FuG, fusiform gyrus; ITG, inferior temporal gyrus; STG, superior temporal gyrus. Statistical maps and ROIs are projected onto segmented and inflated template brain anatomies.

supplementary motor area, right superior parietal lobule, superior frontal gyrus, precuneus, and postcentral gyrus, and bilateral superior and middle occipital gyri, calcarine sulcus, and cuneus. In contrast, alphabetic > logographic revealed no regions that captured more information about the semantic similarity of alphabetic words.

In addition, we performed equivalent ROI analyses to those described previously using a logographic > alphabetic contrast. Figure 5.12B displays the approximate location of our ROIs and whether neural representations were significantly more sensitive to the semantic similarity of logographic or alphabetic spoken pseudowords. Results are presented in Figure 5.13 and Table 5.5 provides additional details including anatomical labels, coordinates, and associated statistics. No ROIs captured more information about the semantic structure of spoken items from either writing system. Nevertheless, our whole-brain analyses did indicate that the extent to which neural representations within different regions encode the semantic structure of newly learned words during listening is modulated by the orthographic transparency of the writing system. Representations were more sensitive to the semantic structure of logographic items in bilateral parietal and occipital areas and left lateralised posterior temporal regions (see Figures 5.12A). These regions have been associated with spoken language processing, lexical phonological representations, and semantic processing (i.e. left middle temporal gyrus and posterior cingulate cortex; Davis & Gaskell, 2009; Binder et al., 2009; Forseth et al., 2018). In addition, representations captured more semantic information about logographic spoken items in regions associated with visual processing and non-lexical orthographic representations (i.e., bilateral superior and middle occipital gyri and calcarine sulci; Levy et al., 2009; Fiebach et al., 2002). No regions captured more semantic information about alphabetic > logographic words.

As one-sample t-tests did not reveal any regions that captured information about the semantic structure of alphabetic or logographic spoken items, we cannot confidently conclude that representations within the regions depicted in Figure 5.12A were more sensitive to the semantic similarity of logographic > alphabetic words. While statistically significant, these differences are driven by negative correlations between neural and predicted similarity structures representing sensitivity to the semantic structure of alphabetic spoken items. Thus, these analyses do not support our

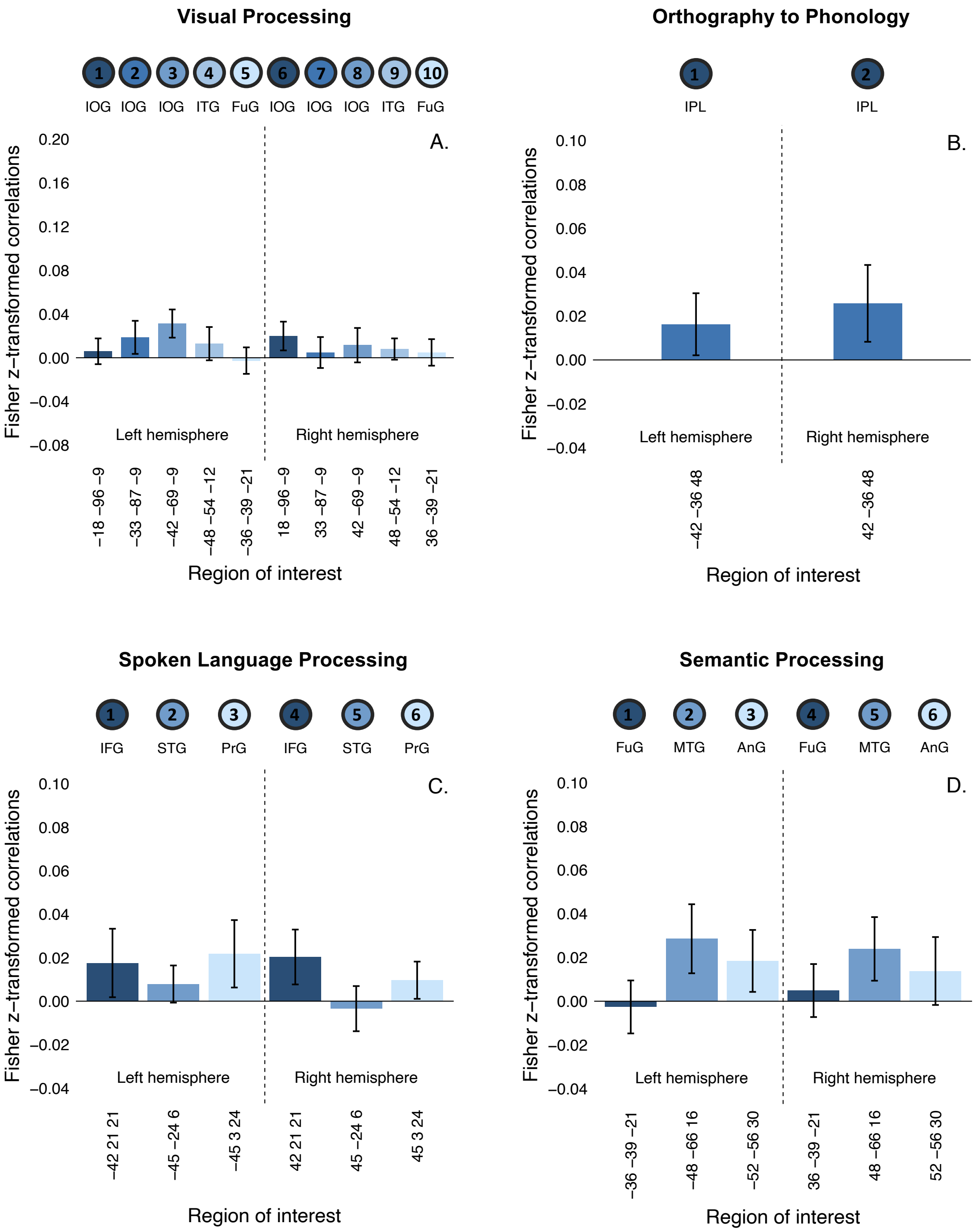


Figure 5.13. RSA Correlations Associated with Paired-Samples t-tests Comparing Neural Sensitivity to the Semantic Similarity of Logographic > Alphabetic Spoken Pseudowords within ROIs

Note. First-level RSA correlations were averaged within each ROI for each writing system before performing paired-samples t-tests using a logographic > alphabetic contrast. Error bars denote within-subjects SE. *p*-values are not Bonferroni corrected; <.001 = ***, <.01 = **, <.05 = *. Abbreviated anatomical labels correspond to Figure 5.12B; coloured discs correspond to Table 5.5A-D and Figures 4.5-4.8 and Tables 4.2-4.5 (see chapter 4). IFG, inferior frontal gyrus; PrG, precentral gyrus; IPL, inferior parietal lobule; AnG, angular gyrus; MTG, middle temporal gyrus; IOG, inferior occipital gyrus; FuG, fusiform gyrus; ITG, inferior temporal gyrus; STG, superior temporal gyrus.

Table 5.5. *Location, Size, and Statistics Associated with ROI Analyses of RSA Maps Comparing Neural Sensitivity to the Semantic Similarity of Logographic > Alphabetic Spoken Pseudowords*

Location (AAL)	Hemisphere	Size (mm)	X	Y	Z	β	t	p	Key
A. Inferior Occipital Cortex	Left	8	-18	-96	-9	.01	.50	.689	①
Inferior Occipital Cortex	Left	8	-33	-87	-9	.02	1.23	.885	②
Inferior Occipital Cortex	Left	8	-42	-69	-9	.03	2.43	.988	③
Inferior Temporal Gyrus	Left	8	-48	-54	-12	.01	.85	.797	④
Fusiform Gyrus	Left	8	-36	-39	-21	.00	-.22	.416	⑤
Inferior Occipital Cortex	Right	8	18	-96	-9	.02	1.51	.928	⑥
Inferior Occipital Cortex	Right	8	33	-87	-9	.00	.34	.631	⑦
Inferior Occipital Cortex	Right	8	42	-69	-9	.01	.73	.764	⑧
Inferior Temporal Gyrus	Right	8	48	-54	-12	.01	.82	.789	⑨
Fusiform Gyrus	Right	8	36	-39	-21	.00	.40	.655	⑩
B. Inferior Parietal Lobule	Left	8	-42	-36	48	.02	-1.15	.869	①
Inferior Parietal Lobule	Right	8	42	-36	48	.03	-1.47	.923	②
C. Inferior Frontal Gyrus	Left	8	-42	21	21	.02	1.12	.862	①
Superior Temporal Gyrus	Left	8	-45	-24	6	.01	.92	.817	②
Precentral Gyrus	Left	8	-45	3	24	.02	1.41	.913	③
Inferior Frontal Gyrus	Right	8	42	21	21	.02	1.61	.939	④
Superior Temporal Gyrus	Right	8	45	-24	6	.00	-.33	.372	⑤
Precentral Gyrus	Right	8	45	3	24	.01	1.13	.864	⑥
D. Fusiform Gyrus	Left	8	-36	-39	-21	.00	-.22	.416	①
Middle Temporal Gyrus	Left	8	-48	-66	16	.03	1.81	.958	②
Angular Gyrus	Left	8	-52	-56	30	.02	1.30	.897	③
Fusiform Gyrus	Right	8	36	-39	-21	.00	.40	.655	④
Middle Temporal Gyrus	Right	8	48	-66	16	.02	1.65	.943	⑤
Angular Gyrus	Right	8	52	-56	30	.01	.89	.809	⑥

Note. Location, size, and statistics associated with visual processing (A), IPL (B; orthography to phonology conversion), spoken language processing (C), and semantic processing (D) ROIs. AAL refers to Automated Anatomical Labelling. β represents the group-level RSA correlation associated with each paired-samples t-test implementing the contrast logographic > alphabetic. p-values are not Bonferroni corrected. Key colours and numbers correspond to the coloured bars and discs within Figure 5.13A-D and the coloured discs within Figures 4.5-4.8 and Tables 4.2-4.5 (see chapter 4).

experimental hypotheses as no regions associated with semantic processing were sensitive to the semantic similarity of newly learned words during listening. The statistical structure of the writing system does not appear to impact on neural sensitivity to the semantic similarity of alphabetic or logographic spoken items.

Overall summary of auditory semantic monitoring

In summary, whilst many brain regions encoded the phonemic structure of the newly learned words during spoken language processing, the extent to which this was the case was not modulated by the orthographic transparency of the writing system. In contrast, representations only encoded the orthographic structure of alphabetic and not logographic spoken words; many regions exhibited greater neural sensitivity to orthographic similarity in the alphabetic system compared to the logographic system. Further, whilst neural sensitivity to the confounded phonemic or orthographic structure of spoken words was more widespread for the alphabetic system, representations only exhibited greater sensitivity to phonemic/orthographic similarity in bilateral superior temporal gyrus. Finally, no regions were sensitive to the semantic similarity of the newly learned words during listening and no clear differences were observed between writing systems. Overall, these analyses indicate that the statistical structure of the writing system only impacts on neural sensitivity to orthographic structure. The systematicity of O-P mappings does not appear to influence whether neural representations encode phonemic or semantic structure during listening.

Visual semantic monitoring

Phonemic and orthographic similarity

We first determined whether the systematicity of O-P mappings influenced the extent to which neural representations encode phonemic structure during reading. Here, we predicted that neural response patterns will only be sensitive to the phonemic similarity of pseudowords from the alphabetic writing system. No regions were expected to exhibit sensitivity to the phonemic structure of logographic written words. Phonemic dissimilarity matrices were computed as 1 minus the proportion of shared sounds between word pairs from within the same phonology. Note that for the alphabetic writing system this is equivalent to an orthographic dissimilarity matrix computed as 1 minus the proportion of shared symbols between word pairs, since there was a systematic, one-to-one mapping between symbols and sounds. To evaluate our hypotheses and identify regions that encoded phonemic structure for both writing systems and separately for the alphabetic and logographic writing system, we compared first-level RSA correlation maps representing neural sensitivity to phonemic structure for all written items, alphabetic written items, and logographic written words to zero using voxel-wise one-sample t-tests. Results are presented in Figure 5.14.

Neural response patterns in bilateral frontal, parietal, temporal, and occipital regions encoded phonemic similarity of written items from across both trained writing systems (see Figure 5.14A). These regions included left superior parietal lobule, cuneus, and cerebellum, right inferior occipital cortex, calcarine sulcus, and postcentral gyrus, and bilateral middle temporal gyri, superior and middle occipital gyri, and precuneus. For the alphabetic writing system, sensitivity to the phonemic/orthographic structure of alphabetic written words only was more widely spread in similar bilateral frontal, parietal, temporal, and occipital regions (alphabetic > 0; see Figure 5.14B). These regions included left insula and precentral gyrus, right superior temporal gyrus, parahippocampal gyrus, cuneus, middle cingulate cortex, and thalamus, and bilateral middle temporal gyrus, superior, middle, and inferior occipital gyri, and calcarine sulcus. For the logographic writing system, no regions captured phonemic similarity.

A direct contrast (paired-sample t-test) revealed that representations were more sensitive to the phonemic structure of alphabetic than logographic written words in bilateral parietal and occipital areas and posterior frontal and temporal regions (alphabetic > logographic; see Figure 5.14C). These regions included left inferior parietal lobule and postcentral gyrus, right superior and middle frontal gyri, inferior temporal gyrus, superior parietal lobule, lingual gyrus, calcarine sulcus, and supplementary motor area, and bilateral middle temporal gyri, fusiform gyrus, superior and middle occipital gyri, inferior occipital cortex, middle cingulate cortex, and precentral gyri. In contrast, logographic > alphabetic revealed that no brain regions captured significantly more information about the phonemic similarity of logographic

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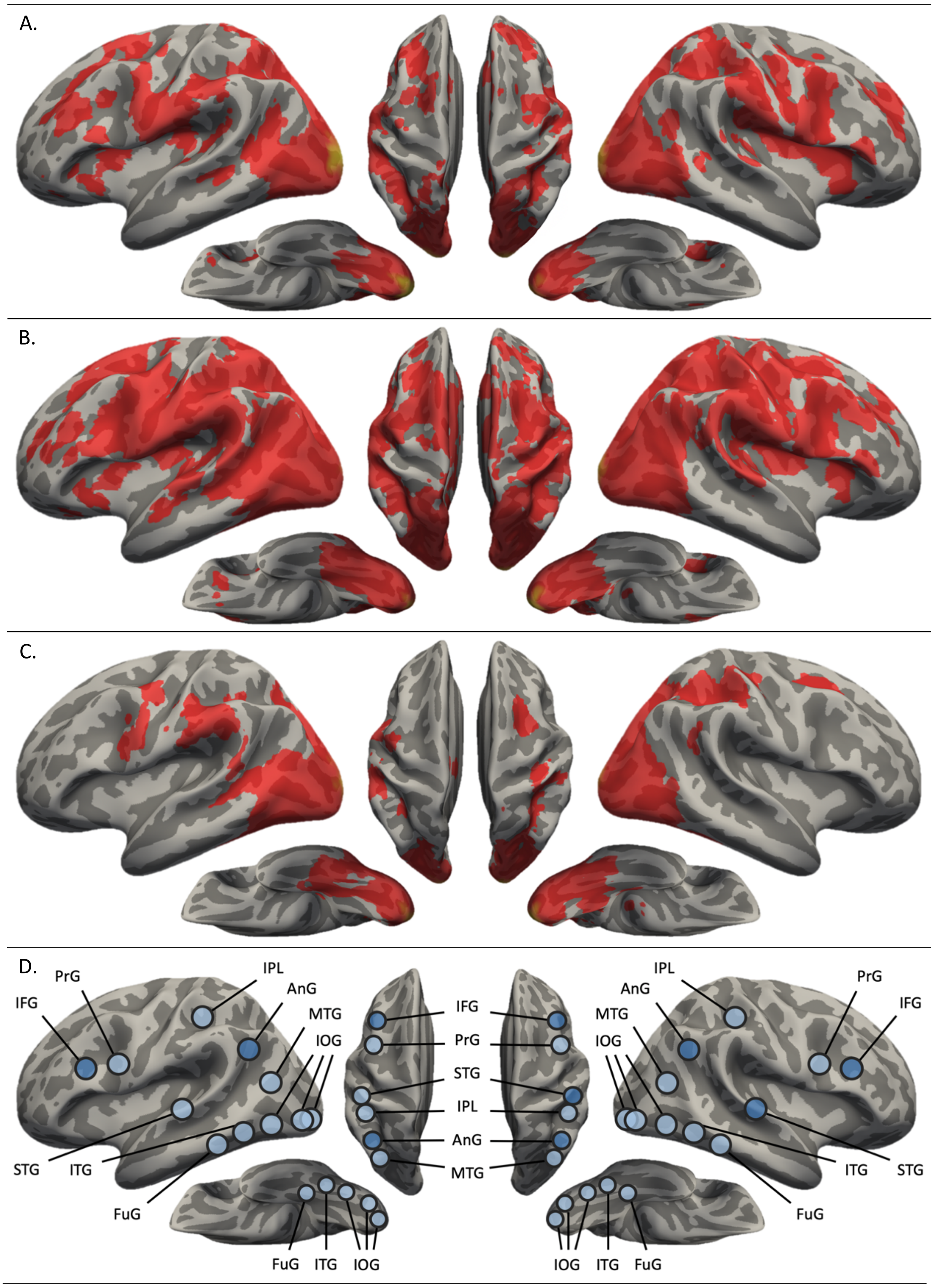
Figure 5.14. Brain regions where representations were (A) sensitive to the phonemic similarity of all trained written pseudowords > 0, (B) sensitive to the phonemic similarity of alphabetic written pseudowords > 0, and (C) more sensitive to the phonemic similarity of alphabetic > logographic written pseudowords. RSA results are TFCE enhanced using permutation testing and thresholded at voxel-wise FWE corrected $p < .05$. (D) Locations of ROIs used to perform ROI analyses on RSA maps. Light blue represents ROIs exhibiting greater neural sensitivity to the phonemic similarity of alphabetic than logographic written pseudowords; dark blue represents ROIs with no differences in sensitivity to the phonemic similarity of alphabetic and logographic written pseudowords (alphabetic > logographic; $p < .05$ without Bonferroni correction). IFG, inferior frontal gyrus; PrG, precentral gyrus; IPL, inferior parietal lobule; AnG, angular gyrus; MTG, middle temporal gyrus; IOG, inferior occipital gyrus; FuG, fusiform gyrus; ITG, inferior temporal gyrus; STG, superior temporal gyrus. Statistical maps and ROIs are projected onto segmented and inflated template brain anatomies.



written words. Combined, these analyses support our hypotheses as they indicate that neural representations only reflect information about the phonemic form of alphabetic written words. This suggests that neural representations only encode the phonemic structure of newly learned words with systematic O-P mappings during reading.

In addition, we performed ROI analyses on first-level correlation maps in regions associated with visual, spoken language and semantic processing, and spelling-sound conversion before conducting paired-samples t-tests using an alphabetic > logographic contrast. Figure 5.14D displays the approximate location of our ROIs and whether neural representations were significantly more sensitive to the phonemic similarity of alphabetic or logographic written pseudowords. Results are presented in Figure 5.15 and Table 5.6 provide additional details including anatomical labels, coordinates, and associated statistics. Representations were more sensitive to the phonemic structure of alphabetic written words in left superior temporal gyrus and bilateral posterior and anterior inferior occipital cortex, posterior and anterior fusiform gyri, inferior temporal gyri, inferior parietal lobule, middle temporal gyri, and precentral gyri. No ROIs captured more information about the phonemic similarity of logographic words.

Overall, these analyses revealed that the extent to which neural representations encode the phonemic structure of newly learned words during reading is modulated by the orthographic transparency of the writing system. Representations were more sensitive to the phonemic structure of alphabetic > logographic words in bilateral parietal and posterior frontal areas and occipital and posterior temporal regions, including vOT (see Figure 5.14C and 5.14D). These regions have been associated with visual and written language processing, orthographic non-lexical and lexical representations, orthography to phonology conversion, phonological lexical representations, phonological output, orthography to semantic conversion, and semantic processing

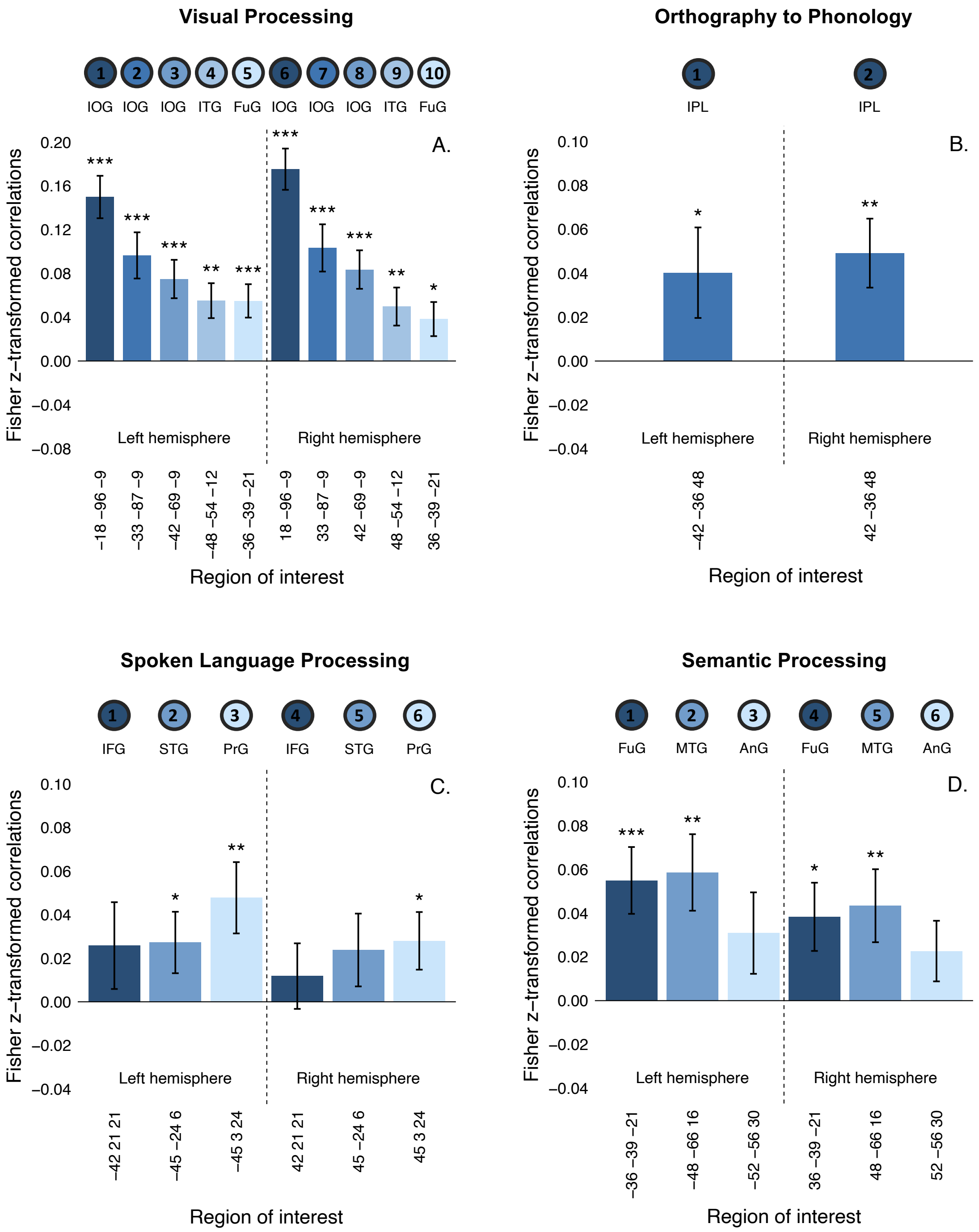


Figure 5.15. RSA Correlations Associated with Paired-Samples t-tests Comparing Neural Sensitivity to the Phonemic Similarity of Alphabetic > Logographic Written Pseudowords within ROIs

Note. First-level RSA correlations were averaged within each ROI for each writing system before performing paired-samples t-tests using an alphabetic > logographic contrast. Error bars denote within-subjects SE. *p*-values are not Bonferroni corrected; <.001 = ***, <.01 = **, <.05 = *. Abbreviated anatomical labels correspond to Figure 5.14D; coloured discs correspond to Table 5.6A-D and Figures 4.5-4.8 and Tables 4.2-4.5 (see chapter 4). IFG, inferior frontal gyrus; PrG, precentral gyrus; IPL, inferior parietal lobule; AnG, angular gyrus; MTG, middle temporal gyrus; IOG, inferior occipital gyrus; FuG, fusiform gyrus; ITG, inferior temporal gyrus; STG, superior temporal gyrus.

Table 5.6. *Location, Size, and Statistics Associated with ROI Analyses of RSA Maps Comparing Neural Sensitivity to the Phonemic Similarity of Alphabetic > Logographic Written Pseudowords*

Location (AAL)	Hemisphere	Size (mm)	X	Y	Z	*β*	*t*	*p*	Key
A. Inferior Occipital Cortex	Left	8	-18	-96	-9	.15	7.73	<.001	①
Inferior Occipital Cortex	Left	8	-33	-87	-9	.10	4.57	<.001	②
Inferior Occipital Cortex	Left	8	-42	-69	-9	.07	4.27	<.001	③
Inferior Temporal Gyrus	Left	8	-48	-54	-12	.06	3.46	.001	④
Fusiform Gyrus	Left	8	-36	-39	-21	.05	3.60	.001	⑤
Inferior Occipital Cortex	Right	8	18	-96	-9	.18	9.30	<.001	⑥
Inferior Occipital Cortex	Right	8	33	-87	-9	.10	4.78	<.001	⑦
Inferior Occipital Cortex	Right	8	42	-69	-9	.08	4.75	<.001	⑧
Inferior Temporal Gyrus	Right	8	48	-54	-12	.05	2.86	.004	⑨
Fusiform Gyrus	Right	8	36	-39	-21	.04	2.46	.011	⑩
B. Inferior Parietal Lobule	Left	8	-42	-36	48	.04	1.95	.032	①
Inferior Parietal Lobule	Right	8	42	-36	48	.05	3.13	.002	②
C. Inferior Frontal Gyrus	Left	8	-42	21	21	.03	1.30	.104	①
Superior Temporal Gyrus	Left	8	-45	-24	6	.03	1.93	.033	②
Precentral Gyrus	Left	8	-45	3	24	.05	2.92	.004	③
Inferior Frontal Gyrus	Right	8	42	21	21	.01	.78	.221	④
Superior Temporal Gyrus	Right	8	45	-24	6	.02	1.42	.084	⑤
Precentral Gyrus	Right	8	45	3	24	.03	2.12	.023	⑥
D. Fusiform Gyrus	Left	8	-36	-39	-21	.05	3.60	.001	①
Middle Temporal Gyrus	Left	8	-48	-66	16	.06	3.35	.001	②
Angular Gyrus	Left	8	-52	-56	30	.03	1.66	.055	③
Fusiform Gyrus	Right	8	36	-39	-21	.04	2.46	.011	④
Middle Temporal Gyrus	Right	8	48	-66	16	.04	2.60	.008	⑤
Angular Gyrus	Right	8	52	-56	30	.02	1.64	.058	⑥

Note. Location, size, and statistics associated with visual processing (A), IPL (B; orthography to phonology conversion), spoken language processing (C), and semantic processing (D) ROIs. AAL refers to Automated Anatomical Labelling. *β* represents the group-level RSA correlation associated with each paired-samples *t*-test implementing the contrast alphabetic > logographic. *p*-values are not Bonferroni corrected. Key colours and numbers correspond to the coloured bars and discs within Figure 5.15A-D and the coloured discs within Figure 4.5-4.8 and Tables 4.2-4.5 (see chapter 4).

(i.e., left superior and inferior temporal gyri, precentral gyrus, and inferior parietal lobule, right lingual gyrus and calcarine sulcus, and bilateral posterior middle temporal gyri, fusiform gyri, and superior, middle and inferior occipital gyri; Martin et al., 2015; Jobard et al., 2003; Purcell et al., 2014; Binder et al., 2009; Jobard et al., 2011; Mechelli et al., 2007; Taylor et al., 2013; Fischer-Baum et al., 2018; Vinckier et al., 2007; Fiebach et al., 2002; Levy et al., 2009). No regions captured phonemic information about logographic written words. Thus, these findings support our hypotheses as the systematicity of O-P mappings influenced whether representations encoded phonemic structure during reading. Regions only encoded the phonemic structure of newly learned written words associated with the alphabetic system.

We aimed to determine whether the systematicity of O-P mappings influenced the extent to which neural representations encode orthographic structure during reading. First, we predicted that neural response patterns will be sensitive to the orthographic similarity of pseudowords from both alphabetic and logographic writing systems. Orthographic dissimilarity matrices were computed as 1 minus the proportion of shared symbols between word pairs from within the same orthography. Note that for the alphabetic writing system this is equivalent to a phonemic dissimilarity matrix computed as 1 minus the proportion of shared sounds between word pairs, since there was a systematic, one-to-one mapping between symbols and sounds. To evaluate our hypotheses and identify brain regions that encoded orthographic structure for both writing systems and separately for the alphabetic and logographic system, we compared first-level RSA correlation maps representing neural sensitivity to orthographic structure for all written items, alphabetic written items, and logographic written items to zero using one-sample t-tests. Results are presented in Figure 5.16.

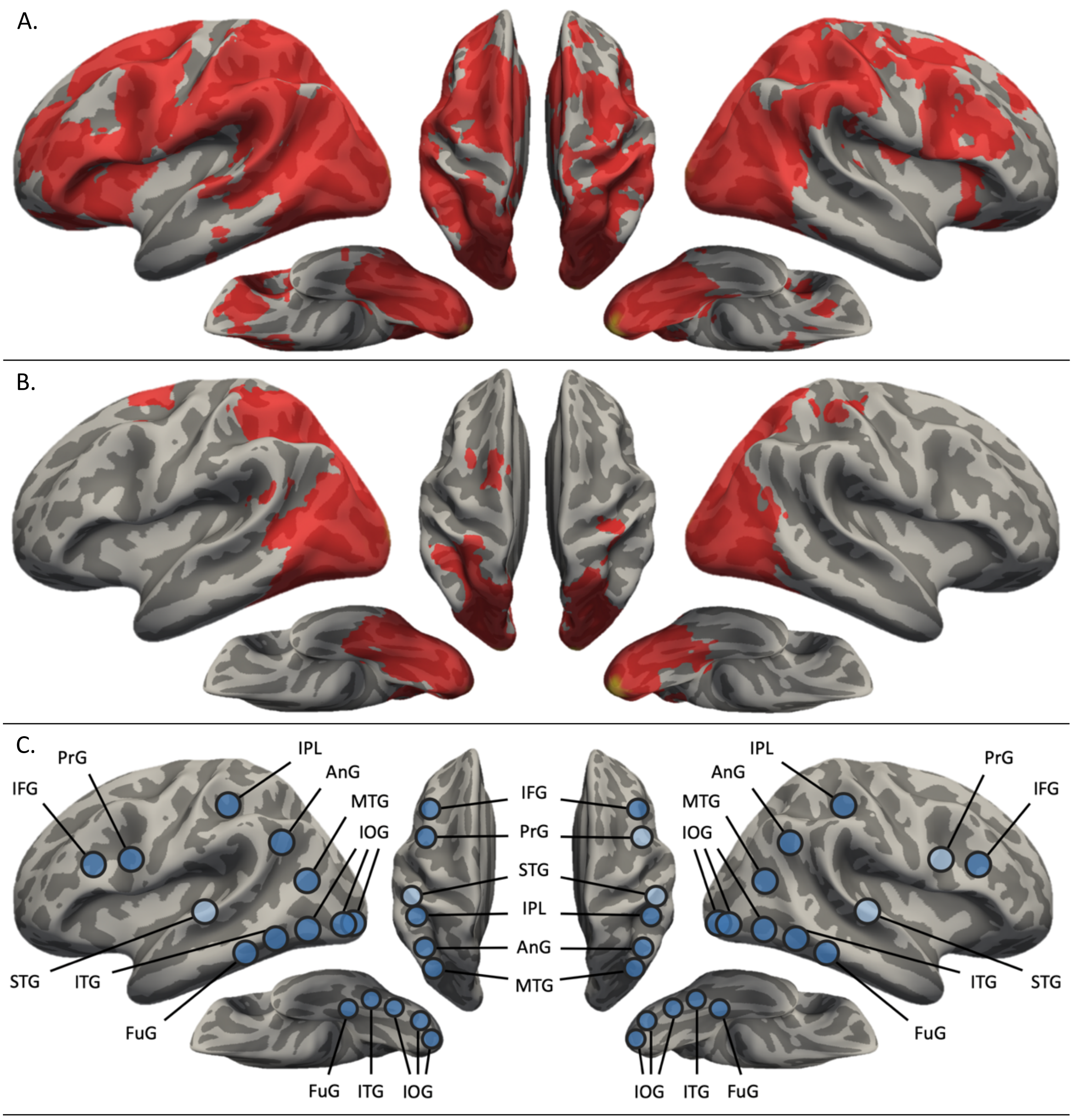


Figure 5.16. Brain regions where neural representations were sensitive to the orthographic similarity of (A) all written pseudowords > 0 and (B) logographic written pseudowords > 0. RSA results are TFCE enhanced using permutation testing and thresholded at voxel-wise FWE corrected $p < .05$. (C) Locations of ROIs used for analyses on RSA correlation maps. Light blue discs represent ROIs exhibiting greater neural sensitivity to the orthographic similarity of alphabetic than logographic written pseudowords; dark blue discs represent ROIs exhibiting no differences in neural sensitivity to the orthographic similarity of alphabetic and logographic written pseudowords (alphabetic > logographic; $p < .05$ without Bonferroni correction). IFG, inferior frontal gyrus; PrG, precentral gyrus; IPL, inferior parietal lobule; AnG, angular gyrus; MTG, middle temporal gyrus; IOG, inferior occipital gyrus; FuG, fusiform gyrus; ITG, inferior temporal gyrus; STG, superior temporal gyrus. Statistical maps and ROIs are projected onto segmented, inflated template brain anatomies.

Neural sensitivity to the orthographic structure of written words from both writing systems was widespread in bilateral parietal and occipital regions. Activation patterns also encoded orthographic structure in bilateral frontal and posterior temporal areas, while sensitivity was more widely distributed in the left hemisphere (see Figure 5.16A). These regions included right cuneus, anterior cingulate cortex, cerebellum, and bilateral middle temporal gyri, superior, middle, and inferior occipital gyri, and calcarine sulcus. As the orthographic dissimilarity matrix was equivalent to a phonemic dissimilarity matrix for the alphabetic writing system, the alphabetic > 0 contrast produced the same results as those in Figure 5.14B (see page 176). Thus, representations were sensitive to the phonemic/orthographic structure of alphabetic words in similar bilateral frontal, parietal, temporal, and occipital regions including left insula and precentral gyrus, right superior temporal gyrus, parahippocampal gyrus, cuneus, middle cingulate cortex, and thalamus, and bilateral middle temporal gyrus, superior, middle, and inferior occipital gyri, and calcarine sulcus.

The statistical contrast Logographic > 0 revealed that neural activation patterns captured the orthographic structure of logographic written words in bilateral parietal and occipital regions, while sensitivity was more widely distributed in left lateralised parietal areas. Left superior frontal, posterior middle and inferior temporal regions also encoded orthographic structure (see Figure 5.16B). These brain regions included left superior frontal gyrus, inferior temporal gyrus, inferior parietal lobule, fusiform gyrus, superior occipital gyrus, inferior occipital cortex, precentral gyrus, and supplementary motor cortex, right lingual gyrus, cuneus, and postcentral gyrus, and bilateral middle occipital gyrus, calcarine sulcus, and cerebellum. Combined, these analyses support our experimental hypothesis as they indicate that representations reflect information about the orthographic form of alphabetic and logographic written words.

Due to a systematic mapping between sounds and symbols, we predicted that regions associated with spoken language and orthographic processing would be more sensitive to the orthographic similarity of alphabetic > logographic written words. No regions were expected to exhibit greater sensitivity to the orthographic structure of logographic > alphabetic words. To evaluate these hypotheses, we compared first-level RSA correlation maps representing neural sensitivity to the orthographic structure of alphabetic and logographic written words using paired-samples t-tests. These whole-brain analyses revealed no significant differences in neural sensitivity to orthographic similarity between the two writing systems. Thus, whilst many regions encoded the orthographic structure of the newly learned words, the extent to which this was the case was not modulated by the orthographic transparency of the writing system.

To maximise sensitivity and specificity, we performed ROI analyses on first-level RSA correlation maps in regions associated with visual, spoken language and semantic processing, and spelling-sound conversion before conducting paired-samples t-tests using an alphabetic > logographic contrast . Figure 5.16C displays the approximate location of our ROIs and whether neural representations were significantly more sensitive to the orthographic similarity of alphabetic or logographic written pseudowords. Results are presented in Figure 5.17 and Table 5.7 provide additional details including anatomical labels, coordinates, and associated statistics. Representations were more sensitive to the orthographic structure of alphabetic written items in bilateral superior temporal gyrus and right precentral gyrus. Left superior temporal gyrus has been associated with spelling-sound conversion, and phonological non-lexical representations (Martin et al., 2015; Jobard et al., 2003; Davis & Gaskell, 2009). No ROIs captured more information about the orthographic similarity of

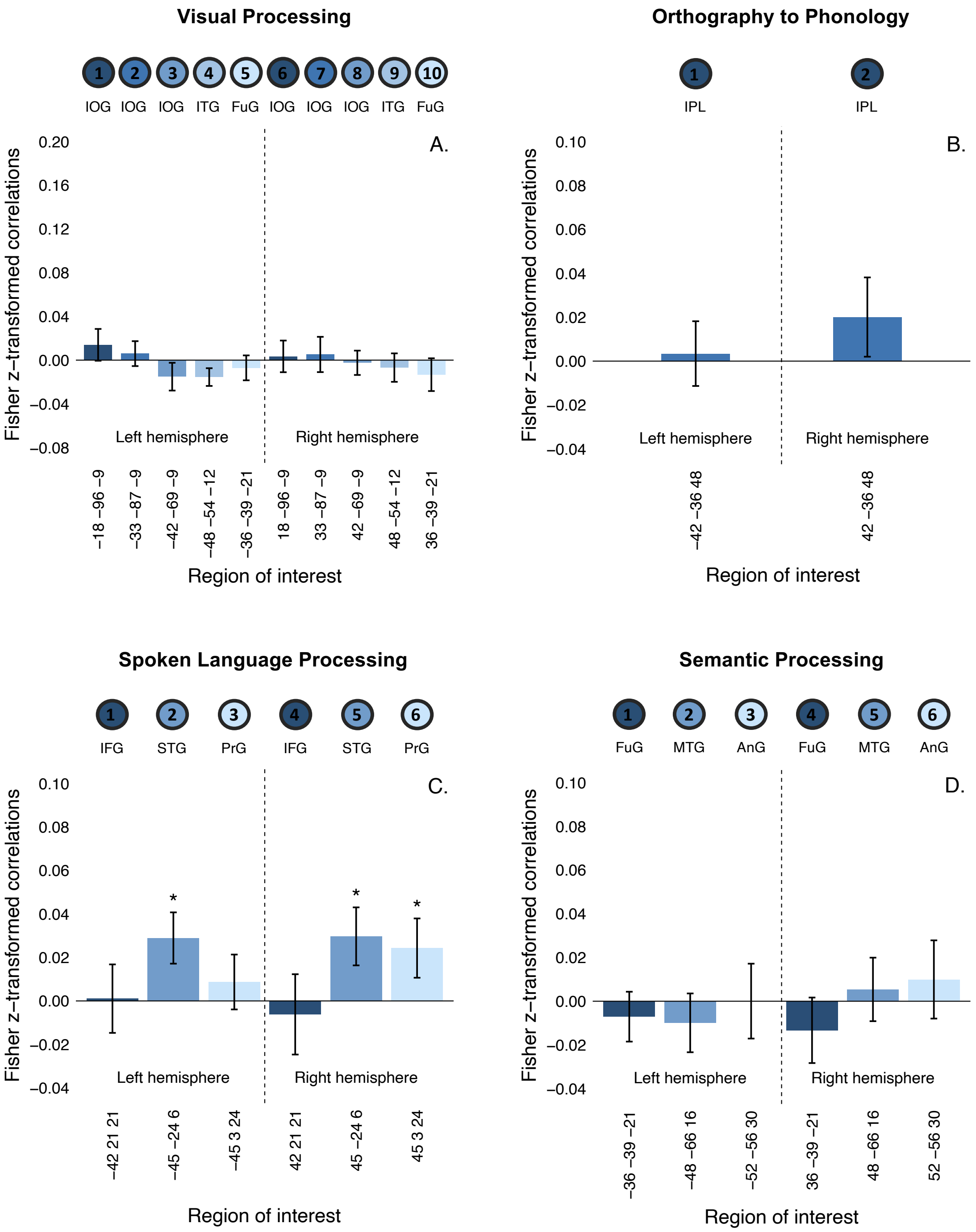


Figure 5.17. RSA Correlations Associated with Paired-Samples t-tests Comparing Neural Sensitivity to the Orthographic Similarity of Alphabetic > Logographic Written Pseudowords within ROIs

Note. First-level RSA correlations were averaged within each ROI for each writing system before performing paired-samples t-tests using an alphabetic > logographic contrast. Error bars denote within-subjects SE. *p*-values are not Bonferroni corrected; <.001 = ***, <.01 = **, <.05 = *. Abbreviated anatomical labels correspond to Figure 5.16C; coloured discs correspond to Table 5.7A-D and Figures 4.5-4.8 and Tables 4.2-4.5 (see chapter 4). IFG, inferior frontal gyrus; PrG, precentral gyrus; IPL, inferior parietal lobule; AnG, angular gyrus; MTG, middle temporal gyrus; IOG, inferior occipital gyrus; FuG, fusiform gyrus; ITG, inferior temporal gyrus; STG, superior temporal gyrus.

Table 5.7. *Location, Size, and Statistics Associated with ROI Analyses of RSA Maps Comparing Neural Sensitivity to the Orthographic Similarity of Alphabetic > Logographic Written Pseudowords*

	Location (AAL)	Hemisphere	Size (mm)	X	Y	Z	β	*t*	*p*	Key
A.	Inferior Occipital Cortex	Left	8	-18	-96	-9	.01	.96	.173	①
	Inferior Occipital Cortex	Left	8	-33	-87	-9	.01	.52	.303	②
	Inferior Occipital Cortex	Left	8	-42	-69	-9	-.02	-1.19	.877	③
	Inferior Temporal Gyrus	Left	8	-48	-54	-12	-.02	-1.91	.966	④
	Fusiform Gyrus	Left	8	-36	-39	-21	-.01	-.62	.729	⑤
	Inferior Occipital Cortex	Right	8	18	-96	-9	.00	.24	.408	⑥
	Inferior Occipital Cortex	Right	8	33	-87	-9	.01	.32	.376	⑦
	Inferior Occipital Cortex	Right	8	42	-69	-9	.00	-.22	.585	⑧
	Inferior Temporal Gyrus	Right	8	48	-54	-12	-.01	-.53	.698	⑨
	Fusiform Gyrus	Right	8	36	-39	-21	-.01	-.89	.808	⑩
B.	Inferior Parietal Lobule	Left	8	-42	-36	48	.00	.23	.409	①
	Inferior Parietal Lobule	Right	8	42	-36	48	.02	1.11	.139	②
C.	Inferior Frontal Gyrus	Left	8	-42	21	21	.00	.07	.474	①
	Superior Temporal Gyrus	Left	8	-45	-24	6	.03	2.45	.011	②
	Precentral Gyrus	Left	8	-45	3	24	.01	.69	.248	③
	Inferior Frontal Gyrus	Right	8	42	21	21	-.01	-.33	.630	④
	Superior Temporal Gyrus	Right	8	45	-24	6	.03	2.23	.018	⑤
	Precentral Gyrus	Right	8	45	3	24	.02	1.78	.044	⑥
D.	Fusiform Gyrus	Left	8	-36	-39	-21	-.01	-.62	.729	①
	Middle Temporal Gyrus	Left	8	-48	-66	16	-.01	-.74	.765	②
	Angular Gyrus	Left	8	-52	-56	30	.00	.00	.499	③
	Fusiform Gyrus	Right	8	36	-39	-21	-.01	-.89	.808	④
	Middle Temporal Gyrus	Right	8	48	-66	16	.01	.37	.357	⑤
	Angular Gyrus	Right	8	52	-56	30	.01	.56	.292	⑥

Note. Location, size, and statistics associated with visual processing (A), IPL (B; orthography to phonology conversion), spoken language processing (C), and semantic processing (D) ROIs. AAL refers to Automated Anatomical Labelling. β represents the group-level RSA correlation associated with each paired-samples *t*-test implementing the contrast alphabetic > logographic. *p*-values are not Bonferroni corrected. Key colours and numbers correspond to the coloured bars and discs within Figure 5.17A-D and the coloured discs within Figure 4.5-4.8 and Tables 4.2-4.5 (see chapter 4).

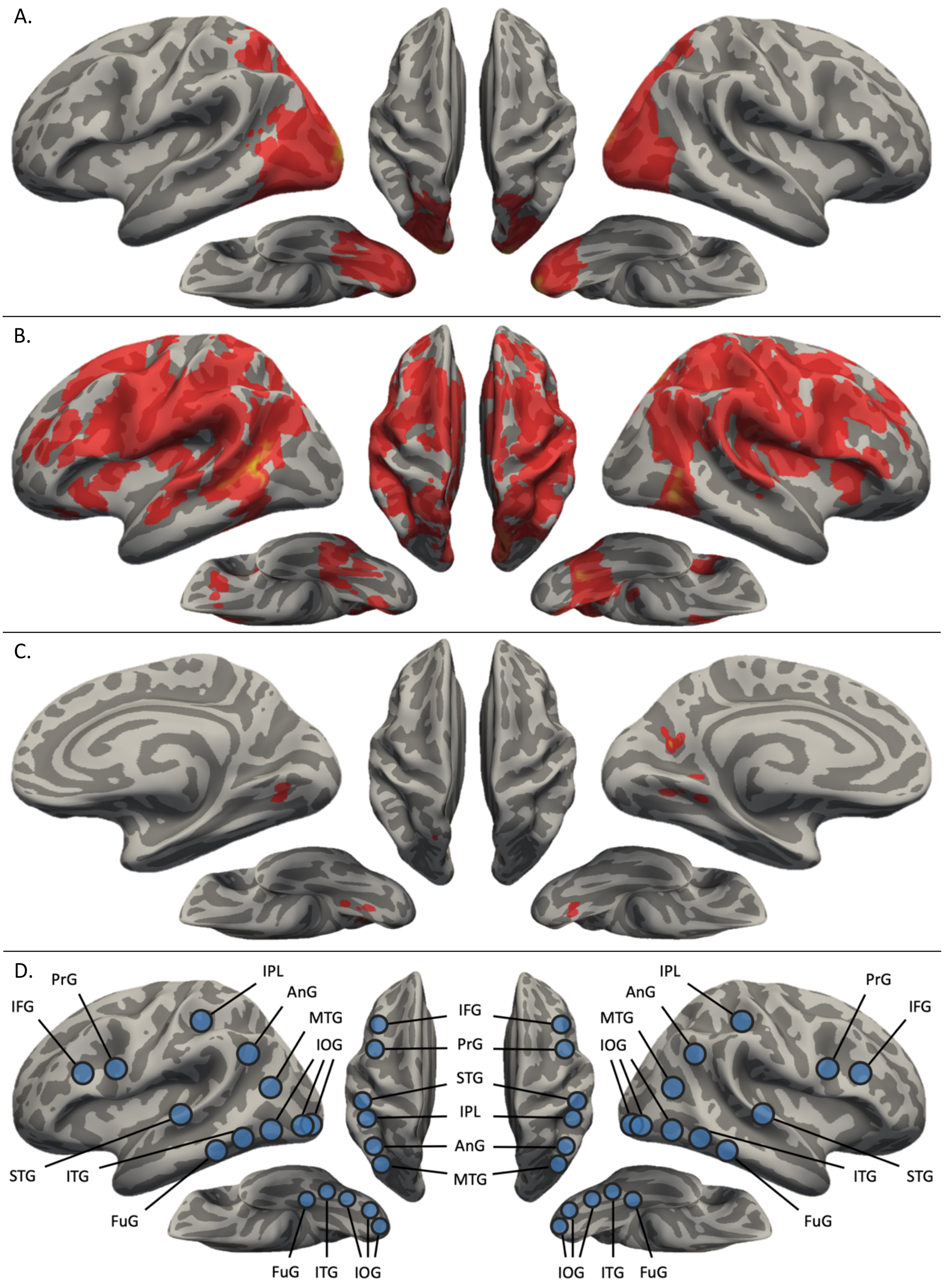
logographic words. Combined, these findings support our hypothesis as the extent to which these regions encode the orthographic structure of written items is modulated by the orthographic transparency of the writing system. Thus, whilst the whole-brain analysis did not reveal any differences in sensitivity to orthographic structure between the two writing systems, such differences were apparent in the ROI analysis.

Alphabetic writing systems are characterised by a systematic, one-to-one mapping between phonemes and graphemes. This relationship between sounds and symbols prevents us for deconfounding neural sensitivity to phonemic and orthographic structure. We aimed to determine whether the systematicity of O-P mappings influenced the extent to which representations encode both phonemic and orthographic structure during reading. For visual semantic monitoring, we hypothesised that neural response patterns will be sensitive to the phonemic and orthographic similarity of both alphabetic and logographic written words. However, an arbitrary, holistic relationship between sounds and spellings requires us to investigate neural sensitivity to phonemic and orthographic structure independently for the logographic writing system.

First-level correlation maps representing sensitivity to phonemic and orthographic similarity were combined for the logographic writing system to create an equivalent to results from the alphabetic system. For each participant, correlations between their neural RDM and phonemic and orthographic dissimilarity matrices were added together at each voxel to generate a combined representation of sensitivity to phonemic and orthographic similarity. To evaluate our hypotheses and identify brain regions that encoded the phonemic and orthographic structure of written words from different writing systems, we compared first-level RSA correlation maps to zero using one-sample t-tests. First, we conducted these analyses using correlation maps representing neural sensitivity to phonemic and orthographic structure for alphabetic written words. Results are presented in Figure 5.18. As the first predicted RDM estimated phonemic and orthographic dissimilarity for the alphabetic writing system, alphabetic > 0 produced the same results as those presented in Figure 5.14B (see page 176).

Equivalent analyses were performed using our combined first-level correlation maps representing neural sensitivity to phonemic and orthographic structure for logographic written words. Activation patterns captured the phonemic and orthographic similarity of logographic written words in fewer bilateral parietal and occipital regions (logographic > 0; see Figure 5.18A). These regions included left lingual gyrus, right middle temporal gyrus, fusiform gyrus, calcarine sulcus, and cuneus, and bilateral superior, middle, and inferior occipital gyri, and cerebellum. Combined, these analyses support our hypothesis as neural representations reflect information about the phonemic and orthographic form of alphabetic and logographic written words.

Figure 5.18. Brain regions where representations were (A) sensitive to the phonemic or orthographic similarity of logographic written pseudowords > 0, (B) sensitive to the phonemic or orthographic similarity of alphabetic but not logographic written pseudowords > 0, and (C) sensitive to the phonemic or orthographic similarity of logographic but not alphabetic written pseudowords > 0. RSA results are TFCE enhanced using permutation testing and thresholded at voxel-wise FWE corrected $p < .05$. (D) Locations of ROIs used for analyses on RSA maps. No ROIs were more sensitive to the phonemic/orthographic similarity of alphabetic than logographic written pseudowords (alphabetic > logographic; $p < .05$ without Bonferroni correction). IFG, inferior frontal gyrus; PrG, precentral gyrus; IPL, inferior parietal lobule; AnG, angular gyrus; MTG, middle temporal gyrus; IOG, inferior occipital gyrus; FuG, fusiform gyrus; ITG, inferior temporal gyrus; STG, superior temporal gyrus. Statistical maps and ROIs are projected onto segmented and inflated template brain anatomies.


A.
B.
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Exclusionary masking

Neural sensitivity to phonemic and orthographic structure appears to be more widely distributed for the alphabetic than the logographic writing system. We decided to explore these differences by isolating regions that only exhibited sensitivity for one writing system. Here, significant voxels within our group-level t-map representing neural sensitivity to the phonemic or orthographic structure of logographic written words were excluded from equivalent first-level correlation maps for the alphabetic system, and vice versa, before conducting one-sample t-tests. Results are presented in Figure 5.18. The statistical contrast alphabetic > 0 revealed that bilateral frontal, parietal and temporal regions, and some occipital areas bordering the temporal and parietal lobes, were only sensitive to the phonemic and orthographic structure of written alphabetic words. These regions included left inferior temporal gyrus, insula, and precentral gyrus, right superior temporal gyrus, fusiform gyrus, lingual gyrus, superior occipital gyrus, inferior occipital cortex, calcarine sulcus, parahippocampal gyrus, cuneus, middle cingulate gyrus, thalamus, and cerebellum, and bilateral middle temporal gyri (see Figure 5.18B). Logographic > 0 identified a small number of significant clusters located in left superior and inferior parietal lobule, superior, middle, and inferior occipital gyri, precuneus and cuneus, right calcarine sulcus, and bilateral fusiform gyri, lingual gyri and cerebellum (see Figure 5.18C). Combined, these analyses confirm that sensitivity to phonemic and orthographic structure is more widely distributed for the alphabetic than the logographic writing system.

Contrasting alphabetic and logographic writing systems

Due to a systematic mapping between sounds and symbols, we predicted that regions associated with spoken language and orthographic processing would be more sensitive to the phonemic or orthographic similarity of alphabetic > logographic written words. No brain regions were expected to exhibit greater sensitivity to the phonemic and orthographic structure of logographic > alphabetic written words. To evaluate these hypotheses, we compared first-level RSA correlation maps representing neural sensitivity to the phonemic or orthographic structure of alphabetic and logographic written items using voxel-wise paired-samples t-tests. Note that no voxels were excluded from these maps. In addition, we performed equivalent ROI analyses to those described previously. Figure 5.18D displays the approximate location of our ROIs and whether neural representations were significantly more sensitive to the phonemic or orthographic similarity of alphabetic or logographic written words. Results are presented in Figure 5.19 and Table 5.8 provide additional details including anatomical labels, coordinates, and statistics. Combined, these analyses revealed no significant differences in neural sensitivity to phonemic and orthographic similarity between the writing systems. Thus, whilst many brain regions encoded the phonemic and orthographic structure of the newly learned words, the extent to which this was the case was not modulated by the orthographic transparency of the writing system.

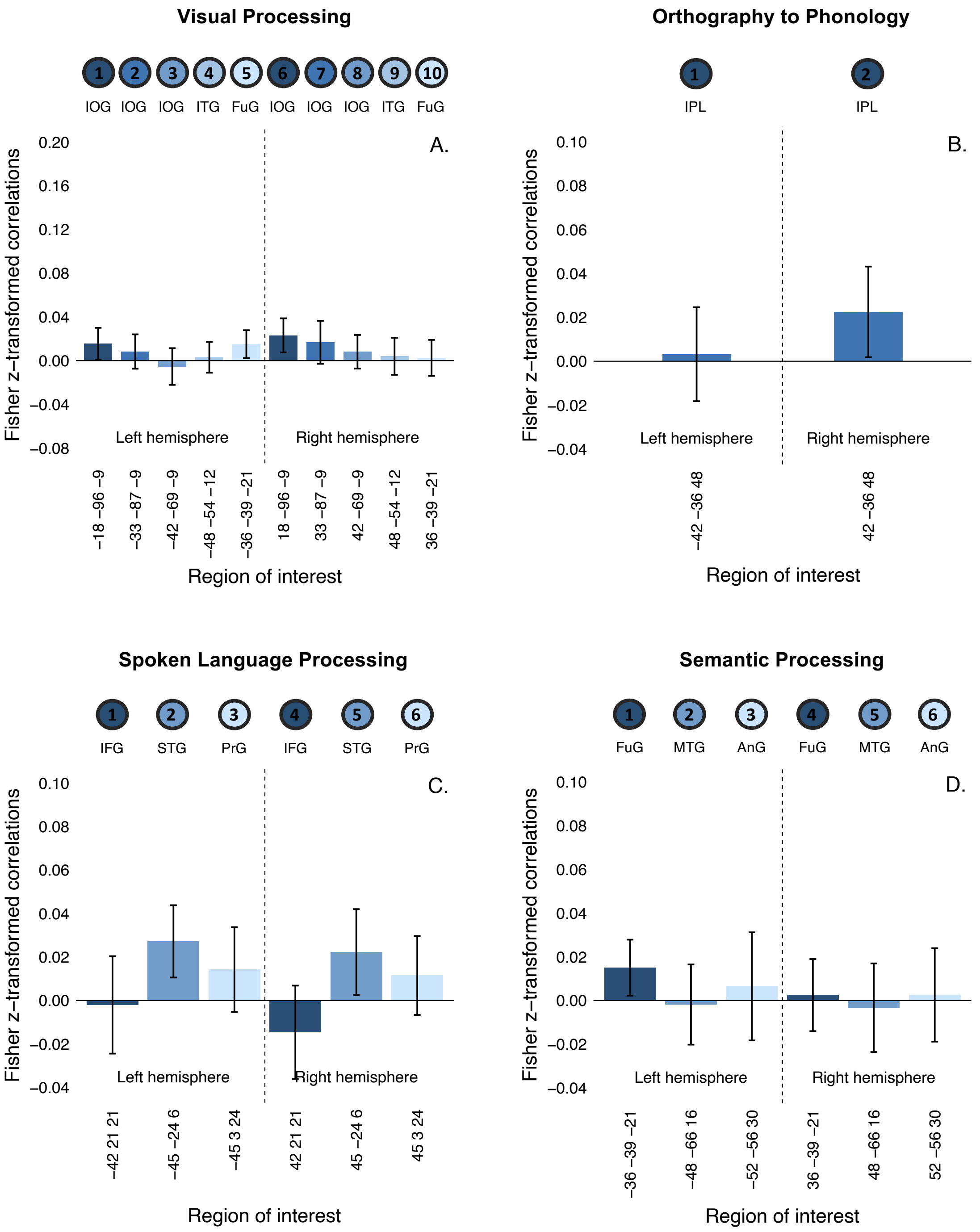

Figure 5.19. RSA Correlations Associated with Paired-Samples t-tests Comparing Sensitivity to the Phonemic/Orthographic Similarity of Alphabetic > Logographic Written Pseudowords within ROIs

Note. First-level RSA correlations were averaged within each ROI for each writing system before performing paired-samples t-tests using an alphabetic > logographic contrast. Error bars denote within-subjects SE. *p*-values are not Bonferroni corrected; <.001 = ***, <.01 = **, <.05 = *. Abbreviated anatomical labels correspond to Figure 5.18D; coloured discs correspond to Table 5.8A-D and Figures 4.5-4.8 and Tables 4.2-4.5 (see chapter 4). IFG, inferior frontal gyrus; PrG, precentral gyrus; IPL, inferior parietal lobule; AnG, angular gyrus; MTG, middle temporal gyrus; IOG, inferior occipital gyrus; FuG, fusiform gyrus; ITG, inferior temporal gyrus; STG, superior temporal gyrus.

Table 5.8. *Statistics Associated with ROI Analyses of RSA Maps Comparing Neural Sensitivity to the Phonemic/Orthographic Similarity of Alphabetic > Logographic Written Pseudowords*

Location (AAL)	Hemisphere	Size (mm)	X	Y	Z	β	t	p	Key
A. Inferior Occipital Cortex	Left	8	-18	-96	-9	.02	1.05	.151	①
Inferior Occipital Cortex	Left	8	-33	-87	-9	.01	.53	.301	②
Inferior Occipital Cortex	Left	8	-42	-69	-9	-.01	-.32	.625	③
Inferior Temporal Gyrus	Left	8	-48	-54	-12	.00	.21	.416	④
Fusiform Gyrus	Left	8	-36	-39	-21	.02	1.17	.126	⑤
Inferior Occipital Cortex	Right	8	18	-96	-9	.02	1.48	.076	⑥
Inferior Occipital Cortex	Right	8	33	-87	-9	.02	.85	.202	⑦
Inferior Occipital Cortex	Right	8	42	-69	-9	.01	.52	.303	⑧
Inferior Temporal Gyrus	Right	8	48	-54	-12	.00	.23	.409	⑨
Fusiform Gyrus	Right	8	36	-39	-21	.00	.15	.441	⑩
B. Inferior Parietal Lobule	Left	8	-42	-36	48	.00	.15	.441	①
Inferior Parietal Lobule	Right	8	42	-36	48	.02	1.09	.143	②
C. Inferior Frontal Gyrus	Left	8	-42	21	21	.00	-.09	.536	①
Superior Temporal Gyrus	Left	8	-45	-24	6	.03	1.64	.058	②
Precentral Gyrus	Left	8	-45	3	24	.01	.73	.236	③
Inferior Frontal Gyrus	Right	8	42	21	21	-.01	-.68	.749	④
Superior Temporal Gyrus	Right	8	45	-24	6	.02	1.13	.136	⑤
Precentral Gyrus	Right	8	45	3	24	.01	.63	.266	⑥
D. Fusiform Gyrus	Left	8	-36	-39	-21	.02	1.17	.126	①
Middle Temporal Gyrus	Left	8	-48	-66	16	.00	-.10	.540	②
Angular Gyrus	Left	8	-52	-56	30	.01	.26	.398	③
Fusiform Gyrus	Right	8	36	-39	-21	.00	.15	.441	④
Middle Temporal Gyrus	Right	8	48	-66	16	.00	-.16	.564	⑤
Angular Gyrus	Right	8	52	-56	30	.00	.12	.453	⑥

Note. Location, size, and statistics associated with visual processing (A), IPL (B; orthography to phonology conversion), spoken language processing (C), and semantic processing (D) ROIs. AAL refers to Automated Anatomical Labelling. β represents the group-level RSA correlation associated with each paired-samples t-test implementing the contrast alphabetic > logographic. p-values are not Bonferroni corrected. Key colours and numbers correspond to the coloured bars and discs within Figure 5.19A-D and the coloured discs within Figure 4.5-4.8 and Tables 4.2-4.5 (see chapter 4).

Semantic similarity

We aimed to determine whether the systematicity of O-P mappings influenced the extent to which neural representations encode semantic structure during reading. For visual semantic monitoring, we predicted that neural response patterns will be sensitive to the semantic similarity of alphabetic and logographic written words. Semantic dissimilarity matrices represented whether the meanings of word pairs from within the same writing system were from the same semantic category (same category = 0, different categories = 1). To evaluate our hypotheses and identify regions that encoded semantic structure for both writing systems and separately for the alphabetic and logographic system, we compared first-level correlation maps representing neural sensitivity to semantic structure for all written words, alphabetic written words, and logographic written words to zero using one-sample t-tests. No regions captured information about the semantic structure of alphabetic or logographic words.

Due to an arbitrary rather than systematic mapping between sounds and symbols, we predicted that regions associated with semantic processing would be more sensitive to the semantic similarity of logographic > alphabetic written words. No regions were expected to exhibit greater sensitivity to semantic structure for the alphabetic > logographic writing system. To evaluate these hypotheses, we compared first-level RSA correlation maps representing neural sensitivity to the semantic similarity of logographic and alphabetic written words using voxel-wise paired-samples t-tests. Results are presented in Figure 5.20. Logographic > alphabetic revealed that neural representations were more sensitive to the semantic structure of logographic written words in two left lateralised clusters in the parietal and occipital lobes (i.e., left superior parietal lobule and left middle occipital gyrus; see Figure 5.20A). In contrast,

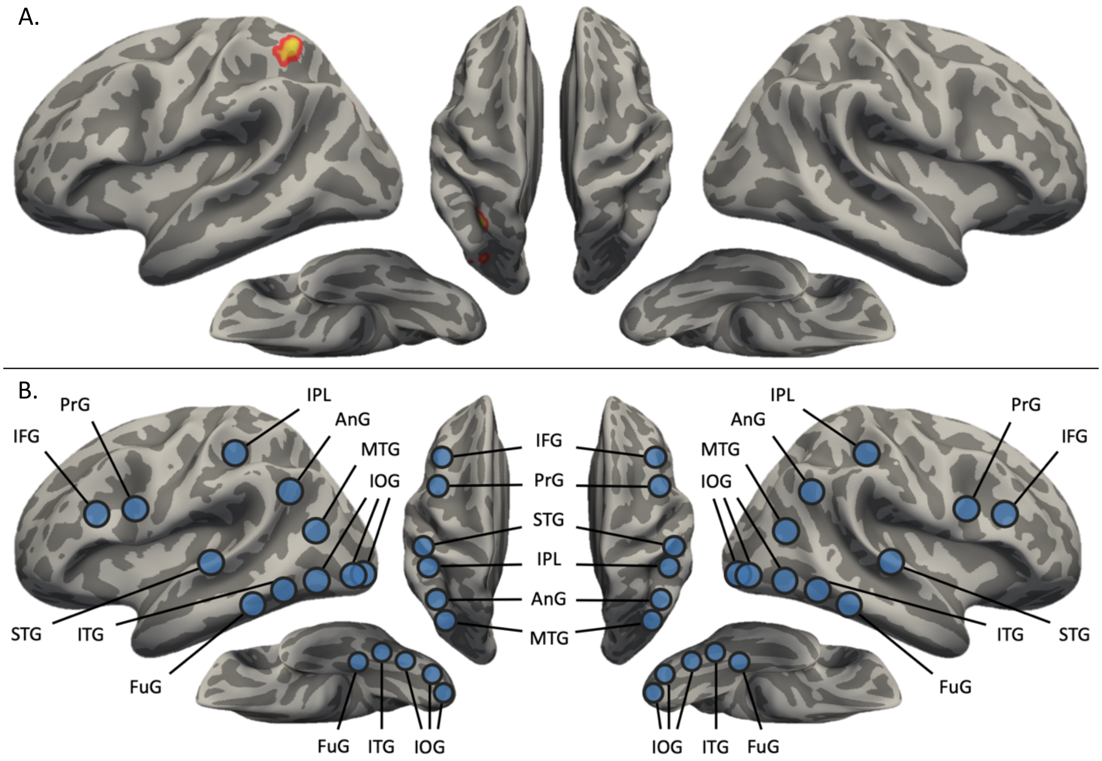

Figure 5.20. Brain regions where neural representations were more sensitive to the semantic similarity of logographic > alphabetic words when participants recalled the meaning of written pseudowords (A). RSA results are TFCE enhanced using permutation testing and thresholded at voxel-wise FWE corrected $p < .05$. (B) Locations of ROIs used to perform ROI analyses on RSA maps. No ROIs were more sensitive to the semantic similarity of logographic > alphabetic written pseudowords ($p < .05$ without Bonferroni correction). IFG, inferior frontal gyrus; PrG, precentral gyrus; IPL, inferior parietal lobule; AnG, angular gyrus; MTG, middle temporal gyrus; IOG, inferior occipital gyrus; FuG, fusiform gyrus; ITG, inferior temporal gyrus; STG, superior temporal gyrus. Statistical maps and ROIs are projected onto segmented and inflated template brain anatomies.

alphabetic > logographic revealed no brain regions that captured significantly more information about the semantic similarity of alphabetic than logographic words.

In addition, we performed equivalent ROI analyses to those described previously using a logographic > alphabetic contrast. Figure 5.20B displays the approximate location of our ROIs and whether neural representations were significantly more sensitive to the semantic similarity of logographic or alphabetic spoken pseudowords. Results are presented in Figure 5.21 and Table 5.9 provide more details including anatomical

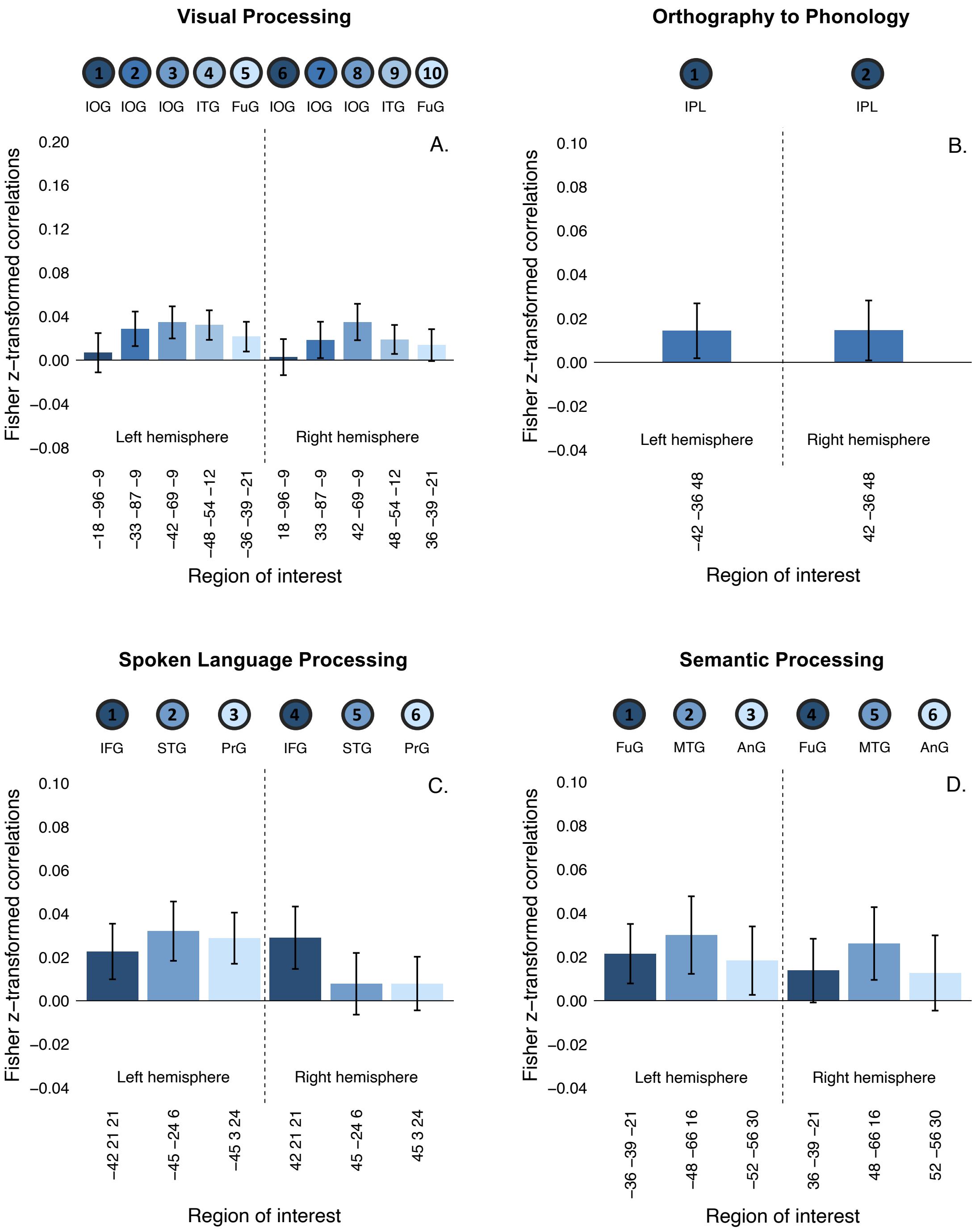

Figure 5.21. RSA Correlations Associated with Paired-Samples t-tests Comparing Neural Sensitivity to the Semantic Similarity of Logographic > Alphabetic Written Pseudowords within ROIs

Note. First-level RSA correlations were averaged within each ROI for each writing system before performing paired-samples t-tests using a logographic > alphabetic contrast. Error bars denote within-subjects SE. *p*-values are not Bonferroni corrected; <.001 = ***, <.01 = **, <.05 = *. Abbreviated anatomical labels correspond to Figure 5.20B; coloured discs correspond to Table 5.9A-D and Figures 4.5-4.8 and Tables 4.2-4.5 (see chapter 4). IFG, inferior frontal gyrus; PrG, precentral gyrus; IPL, inferior parietal lobule; AnG, angular gyrus; MTG, middle temporal gyrus; IOG, inferior occipital gyrus; FuG, fusiform gyrus; ITG, inferior temporal gyrus; STG, superior temporal gyrus.

Table 5.9. *Location, Size, and Statistics Associated with ROI Analyses of RSA Maps Comparing Neural Sensitivity to the Semantic Similarity of Logographic > Alphabetic Written Pseudowords*

Location (AAL)	Hemisphere	Size (mm)	X	Y	Z	*β*	*t*	*p*	Key
A. Inferior Occipital Cortex	Left	8	-18	-96	-9	.01	.38	.645	①
Inferior Occipital Cortex	Left	8	-33	-87	-9	.03	1.81	.959	②
Inferior Occipital Cortex	Left	8	-42	-69	-9	.03	2.35	.986	③
Inferior Temporal Gyrus	Left	8	-48	-54	-12	.03	2.37	.987	④
Fusiform Gyrus	Left	8	-36	-39	-21	.02	1.58	.936	⑤
Inferior Occipital Cortex	Right	8	18	-96	-9	.00	.17	.565	⑥
Inferior Occipital Cortex	Right	8	33	-87	-9	.02	1.11	.861	⑦
Inferior Occipital Cortex	Right	8	42	-69	-9	.03	2.10	.976	⑧
Inferior Temporal Gyrus	Right	8	48	-54	-12	.02	1.43	.917	⑨
Fusiform Gyrus	Right	8	36	-39	-21	.01	.94	.822	⑩
B. Inferior Parietal Lobule	Left	8	-42	-36	48	.01	1.15	.869	①
Inferior Parietal Lobule	Right	8	42	-36	48	.01	1.06	.851	②
C. Inferior Frontal Gyrus	Left	8	-42	21	21	.02	1.77	.955	①
Superior Temporal Gyrus	Left	8	-45	-24	6	.03	2.35	.986	②
Precentral Gyrus	Left	8	-45	3	24	.03	2.45	.989	③
Inferior Frontal Gyrus	Right	8	42	21	21	.03	2.02	.972	④
Superior Temporal Gyrus	Right	8	45	-24	6	.01	.55	.706	⑤
Precentral Gyrus	Right	8	45	3	24	.01	.64	.736	⑥
D. Fusiform Gyrus	Left	8	-36	-39	-21	.02	1.58	.936	①
Middle Temporal Gyrus	Left	8	-48	-66	16	.03	1.69	.948	②
Angular Gyrus	Left	8	-52	-56	30	.02	1.17	.873	③
Fusiform Gyrus	Right	8	36	-39	-21	.01	.94	.822	④
Middle Temporal Gyrus	Right	8	48	-66	16	.03	1.57	.935	⑤
Angular Gyrus	Right	8	52	-56	30	.01	.73	.765	⑥

Note. Location, size, and statistics associated with visual processing (A), IPL (B; orthography to phonology conversion), spoken language processing (C), and semantic processing (D) ROIs. AAL refers to Automated Anatomical Labelling. *β* represents the group-level RSA correlation associated with each paired-samples *t*-test implementing the contrast logographic > alphabetic. *p*-values are not Bonferroni corrected. Key colours and numbers correspond to the coloured bars and discs within Figure 5.21A-D and the coloured discs within Figure 4.5-4.8 and Tables 4.2-4.5 (see chapter 4).

labels, coordinates, and associated statistics. No ROIs captured more information about the semantic structure of written items from either writing system. Nevertheless, our whole-brain analyses did indicate that the extent to which neural representations within different regions encode the semantic structure of newly learned words during reading is modulated by the orthographic transparency of the writing system. Representations were more sensitive to the semantic structure of logographic words in left lateralised parietal and occipital regions (see Figures 5.20A). These brain regions have been associated with spelling-sound conversion, orthographic non-lexical representations, and visual processing (i.e., left superior parietal lobule and middle occipital gyrus; Taylor et al., 2014; Fiebach et al., 2002; Levy et al., 2009). No regions captured more semantic information about alphabetic > logographic words.

As one-sample t-tests did not reveal any regions that captured information about the semantic structure of alphabetic or logographic written items, we cannot confidently conclude that representations within the regions depicted in Figure 5.20A were more sensitive to the semantic similarity of logographic > alphabetic words. While statistically significant, these differences are driven by negative correlations between neural and predicted similarity structures representing sensitivity to the semantic structure of alphabetic written items. Thus, these analyses do not support our experimental hypotheses as no regions associated with semantic processing were sensitive to the semantic similarity of newly learned words during reading. The statistical structure of the writing system does not appear to impact on neural sensitivity to the semantic similarity of alphabetic or logographic written items.

Overall summary of visual semantic monitoring

In summary, neural representations only encoded the phonemic structure of alphabetic written words; many brain regions exhibited greater sensitivity to phonemic similarity compared to the logographic writing system. In contrast, many regions encoded the orthographic structure of written words from both writing systems. However, the extent to which this was the case was only modulated by the orthographic transparency of the writing system in bilateral superior temporal gyrus and right precentral gyrus. Further, neural sensitivity to the confounded phonemic and orthographic structure of written words was more widely distributed for the alphabetic writing system (i.e., within bilateral frontal, parietal and temporal regions, and some occipital areas bordering the temporal and parietal lobes). Nevertheless, no regions exhibited greater sensitivity to phonemic and orthographic similarity compared to the logographic system. Finally, no regions displayed sensitivity to the semantic similarity of written words and no clear differences were observed between writing systems. Overall, these analyses indicate that the statistical structure of the writing system impacts on widespread neural sensitivity to phonemic structure and also orthographic similarity in fewer regions. The systematicity of O-P mappings does not appear to influence whether neural representations encode semantic structure during reading.

Conjunction analysis between visual and auditory modalities

Rueckl et al. (2015) and Chyl et al. (2019) both found speech-print convergence in cortical brain regions associated with phonological and semantic processing and limited variation between different writing systems. Thus, we predicted that neural representations would be sensitive to the confounded phonemic and orthographic structure of alphabetic spoken and written pseudowords in similar regions associated with phonological processing (e.g. left inferior frontal gyri, middle and superior temporal gyri, inferior parietal lobule; Davis & Gaskell, 2009; Taylor et al., 2013). Representations were only predicted to exhibit sensitivity to the phonemic structure of logographic spoken items and the orthographic structure of logographic written items. Thus, we did not expect any brain regions to be sensitive to either the phonemic or orthographic structure of both spoken and written words from the logographic writing system. Finally, given findings from Rueckl et al. (2015) and Chyl et al. (2019), we predicted that representations would be sensitive to the semantic structure of both spoken and written pseudowords from alphabetic and logographic writing systems in similar regions associated with semantic processing (e.g. left inferior frontal gyrus, middle temporal gyrus, inferior parietal lobule; Binder et al., 2009).

To evaluate these hypotheses, we performed conjunction analysis on group-level t-maps resulting from voxel-wise one-sample t-tests to identify regions displaying sensitivity to the orthographic, phonemic or semantic structure of both spoken and written words compared to zero. First, we compared neural sensitivity to the confounded phonemic and orthographic structure of spoken and written alphabetic words. Next, we compared sensitivity to the phonemic structure of spoken and written logographic words before performing equivalent analyses focusing on orthographic structure. In addition, we used conjunction analysis to compare neural sensitivity to the phonemic and orthographic structure of spoken and written logographic words using group-level t-maps resulting from one-sample t-tests performed on our combined first-level correlation maps. Finally, we compared sensitivity to the semantic structure of spoken and written alphabetic words before performing equivalent analyses on logographic words. Results are presented in Figure 5.22.

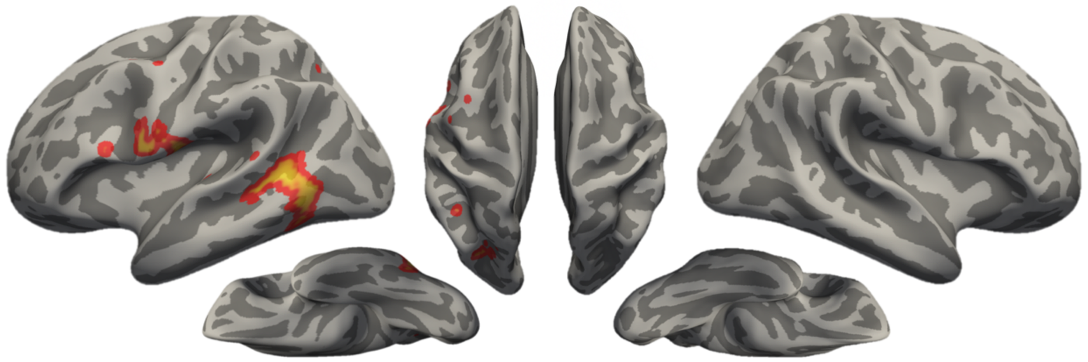

Figure 5.22. Brain regions where representations were sensitive to the phonemic or orthographic similarity of alphabetic spoken and written pseudowords > 0. Neural sensitivity to the phonemic or orthographic similarity of alphabetic written and spoken pseudowords was identified using RSA. Conjunction analysis was performed on results of voxel-wise one-sample t-tests comparing sensitivity to the phonemic or orthographic similarity of alphabetic spoken pseudowords > 0 and written pseudowords > 0. Results are TFCE enhanced without permutation testing and thresholded at voxel-wise FWE corrected $p < .05$. Statistical maps are projected onto segmented and inflated anatomies.

Neural representations were sensitive to the confounded phonemic and orthographic structure of trained alphabetic spoken and written words in left lateralised frontal, temporal, parietal and occipital brain regions (i.e. left middle and inferior frontal (opercularis) gyri, precentral and postcentral gyri, middle and inferior temporal gyri, superior and inferior parietal lobule, superior and middle occipital gyri, rolandic operculum, cuneus, and bilateral superior temporal gyri; see Figure 5.22). These regions have been associated with auditory and spoken language processing, phonological non-lexical and lexical representations, phonological output, in addition to visual and written language processing, orthographic non-lexical representations, spelling-sound and spelling-meaning conversion, and semantic processing (i.e. left middle and inferior frontal gyri, precentral gyri, superior, middle and inferior temporal gyri, superior and inferior parietal lobule, superior and middle occipital gyri; Davis &

Gaskell, 2009; Taylor et al., 2013; Fischer-Baum et al., 2018; Levy et al., 2009; Jobard et al., 2011; Mechelli et al., 2007; Taylor et al., 2014; Martin et al., 2015; Jobard et al., 2003; Fiebach et al., 2002; Purcell et al., 2014; Binder et al., 2009).

No other conjunction analyses revealed speech-sound convergence. No brain regions were sensitive to the phonemic or orthographic structure of both spoken and written logographic words; no regions encoded the semantic structure of alphabetic or logographic spoken and written words. Thus, these analyses only support our hypothesis that neural representations would be sensitive to the confounded phonemic and orthographic structure of alphabetic spoken and written words. Here, speech-print convergence was observed in brain regions associated with phonological processing, including many of those identified by Rueckl et al. (2015) and Chyl et al. (2019; i.e. left inferior frontal gyri, middle temporal gyri, and inferior parietal lobule; Davis & Gaskell, 2009; Taylor et al., 2013). This suggests that these brain regions are sensitive to both phonemic and orthographic structure when recalling the meaning of either spoken or written words associated with an alphabetic writing system.

CHAPTER VI: GENERAL DISCUSSION

Writing systems vary substantially in the extent to which information about the phonological structure of spoken language is encoded by the orthography. As the brain capitalises on systematicity that may exist within the orthography, such differences in orthographic structure may impact on the nature of literacy acquisition and the existing spoken language representations that underpin reading. The purpose of this thesis was to contribute to ongoing debates surrounding the impact of orthographic depth on how the brain solves the problem of reading without dedicated neural hardware and the nature of orthographic effects on spoken language systems. The primary aim was to compare literacy acquisition and spoken language processing across transparent alphabetic and opaque logographic writing systems, incorporating behavioural and both univariate and multivariate neuroimaging methods and analyses. Chapter I reviewed relevant literature, compared theoretical perspectives, and detailed existing research to justify the rationale of our investigation and hypotheses. Chapters II and III outlined the behavioural methods we employed for this experiment and related findings. Chapters IV and V described our neuroimaging methods and associated results. To close, the discussion chapter will evaluate our findings with reference to the content of the literature review to inform our conclusions. First, results will be summarised briefly before moving promptly into interpretation of described findings in the context of previous theoretical and empirical work. Next, the implications of the thesis for real world language processing and learning and existing models of reading will be considered to demonstrate how our findings contribute to the field. Finally, we will discuss the limitations of this work and propose ideas for future research.

6.1. Summary of Empirical Findings

In the present study, we investigated whether differences in orthographic structure impact on reading acquisition and the spoken language representations that underpin reading. We hypothesised that the orthographic transparency of a writing system will determine the division of labour between dorsal (orthography-phonology; O-P) and ventral (orthography-semantic; O-S) pathways of the reading network during reading aloud and comprehension. As alphabetic writing systems feature consistent, one-to-one mappings between symbols and sounds, we predicted that sub-word spelling-sound information would be favoured, strengthening O-P mappings and increasing reliance on the dorsal pathway and neural sensitivity to phonemic and orthographic similarity. Equally, we predicted that spoken language processing would be uniquely impacted by reading acquisition via “online” orthographic co-activation or “offline” phonological restructuring. As logographic systems instead feature arbitrary, whole-word mappings between spelling and sound, we predicted that O-S mappings would be favoured as the more efficient mapping along with increased neural sensitivity to semantic structure. In addition, we explored spelling-sound convergence as a common brain signature of literacy by examining variation between languages with different writing systems (Rueckl et al., 2015; Chyl et al., 2019). Here, we hypothesised that convergent activity would occur within previously identified regions associated with spoken language processing for alphabetic and logographic writing systems.

Overall, behavioural results indicated striking differences in the division of labour between phonological and semantic processes. There was a consistent benefit for O-P tasks for the alphabetic condition while performance on O-S tasks was superior in the logographic condition. Univariate analyses supported our behavioural results.

While the dorsal reading pathway was active for both writing systems, these regions elicited greater neural activity for alphabetic written words. In contrast, whole-brain analyses revealed posterior regions along the ventral pathway were more active for logographic words which was supported by ROI analyses evidencing a shift from greater activity for alphabetic > logographic to logographic > alphabetic written words from posterior to anterior regions along the ventral pathway. RSA indicated that the statistical structure of the writing system impacts on widespread neural sensitivity to phonemic structure and orthographic similarity in fewer brain regions, while no clear differences in neural sensitivity to semantic structure were observed during reading. Finally, convergent activity for spelling and sound was found in a sub-set of previously identified regions (Rueckl et al., 2015; Chyl et al., 2019) irrespective of the nature of the writing system, while neural representations were only sensitive to the confounded phonemic and orthographic structure of alphabetic spoken and written words.

Orthographic transparency appears to impact on the nature of reading acquisition, but our findings do not support evidence suggesting that differences in orthographic structure impact on spoken language systems (e.g., Rastle et al., 2011). Behavioural performance on phonology-semantic (P-S) tasks was not influenced by the nature of the writing system. Univariate results were consistent with these findings as, while brain regions associated with phonological and semantic processing were active for alphabetic and logographic spoken words, no evidence of orthographic co-activation or phonological restructuring was observed for the alphabetic system. Finally, RSA revealed that, whilst many regions encoded the phonemic structure of the newly learned words during spoken language processing, the extent to which this was the case was not modulated by the writing system. Further, neural representations only encoded the orthographic structure of alphabetic spoken words and, while sensitivity to the confounded phonemic/orthographic structure of spoken words was more widespread for the alphabetic system, representations only exhibited greater sensitivity to phonemic/orthographic similarity in bilateral superior temporal gyrus. Finally, no differences in sensitivity to semantic structure were observed during listening.

6.2. Orthographic Depth and Reading Acquisition

Overall, behavioural and neuroimaging results consistently support the division of labour hypothesis and validate the Triangle model of reading (Plaut et al., 1996; Harm & Seidenberg, 2004). Although sounds and meanings of written words can be jointly determined by both reading pathways, our behavioural findings indicate that the nature of the writing system determines the division of labour between direct (O-P) and phonologically mediated (O-P-S) pathways during learning, and consequently reading aloud and comprehension (Taylor et al., 2017). Participants may have read alphabetic written words aloud by accessing phonology directly from orthography while accessing semantic meaning from orthography via phonology. Equally, the logographic writing system appeared to favour arbitrary, whole-word O-S mappings during reading acquisition. Univariate findings are consistent with our behavioural results and indicated that the alphabetic writing system capitalised on systematic, componential O-P mappings and favoured the dorsal reading pathway. Moreover, the logographic writing system favoured arbitrary, holistic O-S mappings during reading acquisition and the ventral pathway. Further, RSA results indicated that, while neural representations reflect information about the orthographic form of alphabetic and logographic written words, they only reflect information about the phonemic form of alphabetic written words. This suggests that representations only encode the phonemic structure of newly learned words with systematic O-P mappings during reading. Equally, RSA revealed that neural representations were only sensitive to the confounded phonemic and orthographic structure of trained alphabetic spoken and written words in left lateralised frontal, temporal, parietal and occipital regions.

Such findings consequently support previous empirical research evidencing a ventral reading pathway underpinning semantic (O-S) processes. ROI analyses evidenced a shift from greater neural activity for alphabetic > logographic written words in the most posterior ROIs along the ventral pathway to logographic > alphabetic in the most anterior ROI. Thus, our findings indicate that participants utilised the reading network in different ways to learn the artificial writing systems, suggest that direct print-meaning processes (i.e., identifying meaning using item-specific knowledge and whole-word information) are underpinned by a processing hierarchy along the ventral stream, and are consistent with Taylor et al. (2019) and Vinckier et al's (2007) description of a processing hierarchy along posterior to anterior vOT. In fact, when compared to Taylor et al’s (2013) contrast of neural activation for words and pseudowords, our alphabetic and logographic orthographies are well matched for difficulty and visual form. For word > pseudoword contrasts, we can never be certain that activation reflects reduced difficulty (less deflection from resting baseline) for words than pseudowords, or if it genuinely reflects a difference in processing style. With our study, we know that the logographic language is at least as hard as the alphabetic language, so it cannot be that observed affects are due to difficulty.

Equally, our findings support research evidencing a dorsal reading pathway which underpins phonological (O-P) processes (Bolger et al., 2005; Bouhali et al., 2014; Roberts et al., 2013). Whole brain analyses are consistent with those from a recent meta-analysis that found greater activation for pseudowords > English words along the indirect dorsal pathway. Taylor et al. (2013) revealed that these brain regions consistently display increased activity for alphabetic pseudowords than known English words. In addition, our findings are consistent with Smith et al. (2021) computational implementation of the Triangle model of reading. Here, orthographic transparency influenced how the model solved reading comprehension and reading aloud and the continued operation of the reading system following training. Specifically, the ratio between O-P-S to O-S was much greater for orthographically transparent than opaque writing systems during reading comprehension. Moreover, the ratio between O-P to O-S-P was much greater for transparent than opaque writing systems during reading aloud. In general, our results also support Mei et al. (2014) who revealed distinct pathways for phonological access via grapheme-to-phoneme and whole word mappings. However, we observed no evidence was to support the strategy-shift hypothesis. Mei et al. (2014) found that reading strategy for alphabetic orthographies shifted from assembled (O-P) to addressed (O-S) with continued practice, a phenomenon which may be present for real world language learning.

Nevertheless, inconsistent findings exist within the thesis from different tasks that do not support the division of labour hypothesis. During O-P training tasks, verbal RTs were faster for the alphabetic writing system, but participants selected written pseudowords from all items more efficiently for the logographic system. On O-S training tasks, a benefit existed for the logographic writing system in terms of speed while accuracy was initially higher for the alphabetic writing system. Furthermore, participants could more accurately identify trained pseudowords from the alphabetic condition for Visual Lexical Decision during testing. Moreover, RSA analyses did not support one of our experimental hypotheses as no regions associated with semantic processing were sensitive to the semantic similarity of newly learned words during reading. The statistical structure of the writing system did not appear to impact on neural sensitivity to the semantic similarity of alphabetic or logographic written items. Finally, univariate conjunction analysis revealed speech-print convergence in a sub-set of regions identified by Rueckl et al. (2015) and Chyl et al. (2019) as a common signature for reading proficiency, irrespective of the nature of the writing system. Nevertheless, spelling-sound convergence was only observed in left inferior frontal regions, not middle to superior temporal gyri or inferior parietal lobule.

6.3. Orthographic Effects on Spoken Language Processing

Overall, both our behavioural and neuroimaging results indicated no effect of orthographic transparency on existing spoken language systems. Thus, no clear evidence was found to support the theoretical perspective that the nature of an orthographic system impacts on phonological processing and spoken language representations. Specifically, no evidence of phonological restructuring or online orthographic co-activation was observed for the alphabetic writing system; no regions associated with orthographic processing were active for alphabetic spoken words, nor were regions associated with phonological and orthographic processing more active for alphabetic than logographic spoken words. Moreover, RSA revealed that, whilst many brain regions encoded the phonemic structure of the newly learned words during spoken language processing, the extent to which this was the case was not modulated by the orthographic transparency of the writing system. Equally, while neural sensitivity to the confounded phonemic/orthographic structure of spoken words was more widespread for the alphabetic writing system, representations only exhibited greater sensitivity to phonemic/orthographic similarity in bilateral superior temporal gyrus. However, these brain regions are not implicated in orthographic processing and have instead been associated with auditory processing and non-lexical phonological processing (Davis & Gaskell, 2009). Finally, no regions were sensitive to the semantic similarity of spoken words and no clear differences were observed between writing systems. Thus, the structure of the writing system does not appear to impact on neural sensitivity to the semantic similarity of alphabetic or logographic spoken words.

These findings support previous research that found no evidence of orthographic effects on speech perception and production (Damien & Bowers, 2009). Equally, while Smith et al. (2021) observed that the structure of phonological representations was impacted by literacy acquisition in some orthographic systems in both the presence (online co-activation) and absence of orthographic information (offline phonological restructuring), a graded effect of orthographic transparency was only found during reading comprehension tasks that required orthographic activation. No orthographic effect was found during semantic comprehension tasks that do not cause orthographic activation. Such findings are consistent with this thesis as they question whether orthographic representations are co-activated during speech perception. However, adjudicating between orthographic co-activation (where orthographic information is activated by spoken language representations) and phonological restructuring (where phonological representations are shaped by literacy) accounts is challenging without observing clear orthographic effects on phonological processing ourselves.

It is possible that both human and computer simulations would ultimately observe potentially subtle orthographic effects on spoken language systems by introducing drastically longer training periods. Such an approach would compare more favourably to real world language learning. In fact, inconsistent findings exist within the thesis from different tasks that lend some support to the theoretical perspective that orthogaphic transparency impacts on spoken language. No main effects of writing system were observed on P-S training tasks (Picture Naming and Picture Search) but consistent interactions between writing system and training day indicated that accuracy improved more quickly for the transparent alphabetic system (while performance converged by the end of training). Equally, the nature of the writing system exerted a subtle impact on phonemic awareness as accuracy was higher for the alphabetic condition on Phoneme Reversal during testing, although this effect was driven by two participants who performed poorly on the logographic condition.

Behavioural and neuroimaging findings do not provide clear support for previous research evidencing orthographic effects on spoken language. For example, Morais et al. (1979) concluded that phonemic awareness does not develop spontaneously during childhood and requires an individual to learn to read an alphabetic writing system. Equally, Seidenberg and Tanenhaus (1979) demonstrated we are faster to judge the similarity of two spoken words when they are spelled similarly than when they are spelled differently. Rastle et al. (2011) observed orthographic involvement in speech perception and production tasks that do not explicitly require orthographic processing having manipulated spelling-sound consistency. Finally, Damian & Bowers (2003b) similarly concluded that orthographic information may be activated during speech production while Brennan et al. (2012) concluded that the phonological awareness network and neural processing of phonology is only enhanced by learning to read transparent alphabetic writing systems. Nevertheless, evidence suggesting that orthographic information impacts on spoken language may reflect metalinguistic knowledge rather than properties of tasks used to measure speech processing.

6.4. Main Implications of the Thesis

Overall, the findings generated by this thesis make a significant contribution to the study of literacy acquisition and the subsequent nature of spoken language processing. Based on the Triangle model of reading (Harm & Seidenberg, 2004), we conducted an artificial language learning study to investigate how different orthographic systems impact on reading acquisition and existing spoken language systems. First, our findings support defining characteristics and proposal made by the Triangle model, evidencing direct and indirect, phonologically mediated reading pathways. Here, we concluded that different reading pathways were favoured depending on orthographic transparency of the writing system. Thus, our results suggest that different strategies are used to learn alphabetic and logographic writing systems and that orthographic transparency can impact on the division of labour and underlying representations (Plaut et al., 1996). Second, our investigation adds to existing computational evidence supporting the notion that the Triangle model is effective as a universal framework of reading that can be successfully applied to the wide range of orthographic systems (see section 1.2). Consequently, our findings indicate that multiple models are not required to account for the wide range of extant orthographic systems. Thus, the Triangle model may provide a more accurate and comprehensive account of reading than the DRC model which focuses on skilled English word reading (Coltheart et al., 2001).

Third, our human simulation reveals a strong match to computational simulations implementing the Triangle model (Smith, 2021). These finding consequently suggest that human and model simulations, while quite distinct in their nature and levels of analysis, can successfully work together to show how important characteristics (e.g., input, approaches to training, prior knowledge) can influence learning. Fourth, as neuroimaging analyses validated our task and method (written words activated brain regions associated with visual and orthographic processing while regions associated with speech and phonological processing were activated by spoken words), this study supports the ascertain that artificial orthography methods constitute an effective approach for investigating real world language learning (Taylor et al., 2017). Fifth, given the prevalence of inconsistent findings associated with previous work, this thesis contributes to ongoing debates about the existence and nature of orthographic effects on phonological processing and spoken language. That such a highly controlled training study observed no clear impact of literacy acquisition on spoken language systems indicates that further research must pursue a comprehensive understanding of key variables that potentially influence whether an orthographic effect on spoken language processing exists and the nature of underlying cognitive mechanisms.

In addition, this study aimed to add to our understanding of literacy acquisition and the spoken language systems that underpin reading by broadly simulating language learning in humans. However, to conduct such an elaborate study, compromises were made including a sample consisting of only monolingual native English speakers. While this approach may have implications for the generalisation of our results (see section 6.5) it means our study most closely simulates second language learning in adults. Equally, results suggests that second language learners favour O-P mappings when learning to read alphabetic languages and O-S mappings for logographic languages. We suggest that such findings have beneficial implications for reading instruction and future education practices, perhaps indicating that O-P mappings should be promoted for transparent alphabetic writing systems (see Taylor et al., 2017) while emphasising O-S mappings may be the most effective for opaque logographic systems. Perhaps a graded shift in the ratio between the degree of O-P and O-S training would be most successful for writing systems falling between the extreme ends of the spectrum of orthographic depth tested in the study. Importantly, a comprehensive understanding of the complex processes involved in reading acquisition and possible consequences for spoken language will help inform best practices for reading instruction across different writing systems, improving levels of global literacy. We consider any contributions this study makes to literacy levels its most important implication. Successfully acquiring literacy in childhood is fundamentally important for engaging with the modern world and may have profound consequences for an individual's quality of life. Banking, interpreting legal documents, giving signed permission and informed consent are but a few examples of key aspects of everyday life that are only made possible via access to effective reading instruction.

6.5. Limitations and Future Directions

The present study implemented a robust and highly intricate experimental design. Training participants on artificial orthographies afforded a very high degree of control over stimulus properties (i.e., what is learned and how it is learned) and participant's prior knowledge. This approach enabled a uniquely clean experimental manipulation by comparing perfectly transparent and opaque orthographies while controlling semantic and phonological associations. Extensive counterbalancing reduced the possibility that any effects of the writing system could be ascribed to idiosyncratic aspects of items while any impact of existing semantic knowledge was accounted for by including semantic object as a random factor within linear-mixed effects models. Equally, the high level of methodological control facilitated a within-subjects design where all participants learned both languages in a counterbalanced order, thereby avoiding confounding variables associated with between-item designs (e.g., Mei et al., 2014). Crucially, all participants learned both writing systems to a high degree of accuracy (above 90% for all tasks) and showed continual increase in speed. Further, while data collection was completed over an unprecedented period (13 days), this advantage introduced potential weekend effects on learning. However, it's unclear whether learning was more obstructed by the opportunity to forget acquired knowledge or benefitted by the opportunity for memory consolidation. Finally, neuroimaging analyses validated our method (i.e., the task performed in the scanner and our analyses appear to be sensible), as written words from both writing systems activated brain regions associated with visual and orthographic processing while regions associated with phonological and semantic processing were activated by spoken words.

Despite the many benefits afforded by our experimental design, notable limitations exist that must be discussed. First, all participants were monolingual native English-speaking adults. The nature of our sample limits the ability to generalise results to monolingual speakers of other languages that do not feature deep alphabetic writing system (see section 1.2) and bi-lingual speakers of languages with similar or highly distinct writing systems. Participants began with considerable prior knowledge and experience of learning a specific type of language that functions quite differently to languages with other writing systems. Further, as participants were adults, we cannot make truly confident conclusions about the nature of literacy acquisition during childhood without prior knowledge of an existing language. Equally, bilingualism potentially impacts on existing monolingual language systems in ways that could influence the subsequent acquisition of highly simplistic alphabetic and logographic writing systems. Further, 24 participants constitute a very limited sample size to achieve a desirable statistical power for our analyses and must be considered when interpreting results. Nevertheless, decisions regarding the nature of our sample were highly intentional and justified by the neuroimaging elements of this study.

As we attempted to test our hypotheses across participants, it was imperative that a level of uniformity was achieved to support our neuroimaging analyses. Central to our investigation was the premise that different writing systems may impact on written and spoken language processing and for these reasons we needed to test participants who had comparable prior language experience. Similarly, all participants were also right-handed, with no history of hearing impairment, uncorrected visual impairment, or learning difficulties to ensure uniformity. We anticipated it would be easier to recruit adults than children and that adults would have greater discipline to stay still and pay continuous attention to a monotonous task while neural responses were recorded within an fMRI scanner (important variables for neuroimaging analyses). Similarly, English-speaking participants were chosen as it would be easier to recruit them to participate in the study. Finally, due to the considerable financial costs associated with neuroimaging studies, our sample was limited to 24 participants.

Benefitted by this investigation's dedication to open science, future research could focus on replicating our study with monolingual speakers of logographic writing systems (i.e., Chinese and Japanese Kanji) to understand whether our findings are unique to English speaking adults learning to read a somewhat familiar alphabetic and unfamiliar logographic language. Perhaps participants with prior language experience centring around a logographic writing system would produce different results as they would instead learn an unfamiliar alphabetic and somewhat familiar logographic language. Equally, future research could test whether our results are replicated by children with considerably less experience with spoken and, perhaps very little experience with, written language. Finally, it would be valuable to investigate the impact of bilingualism on learning new languages with different writing systems, ideally accounting for all combinations of extant languages and writing systems, although it would be challenging to achieve the uniformity previously discussed. Such an investigation would examine the generalisability of our results, how informative they are for reading acquisition during childhood, and how different types of prior experience with one or more languages with distinct writing systems would impact on the nature of reading acquisition and consequences for spoken language systems.

Previous research has found artificial languages to compare favourably with English word reading. Taylor et al. (2017) observed a strikingly similar spatial distribution of neural activation for an artificial alphabetic orthography and English word reading. Moreover, our univariate results were consistent with previous research utilising artificial orthography methods and regions activated when words written in natural languages with alphabetic writing systems are read by adults (Taylor et al., 2017; Taylor et al., 2019). These results evidence the viability of artificial orthography methods and support the validity of our results. In addition, recently learned artificial orthographies appear to evoke stronger neural activity than native languages (Taylor et al., 2013). Thus, we are confident artificial orthography methods constituted a rigorous approach to investigating whether written and spoken language processing differences can arise from the statistical structure of a writing system. These methods also afforded a high degree of experimental control which enabled us to create artificial languages with writing systems at extreme ends on the spectrum of orthographic transparency, facilitating an especially clean experimental manipulation. Opting for maximally distinct conditions for our central independent variable gave us the best possible chance of observing potentially subtle consequences of orthographic depth on reading acquisition and spoken language systems, effects that may not have reached significance if shallow and deep alphabetic orthographies were compared. However, while highly simplified artificial orthographies designed to be maximally distinct with regards to orthographic similarly share commonalities with real world languages, intentional compromises and omissions prevent them from being truly naturalistic.

As we aimed to achieve the cleanest experimental manipulation possible by creating artificial orthographies at extreme ends on the spectrum of orthographic transparency, one writing system was perfectly transparent and the other was perfectly opaque. This is the first example of how our artificial orthographies were not naturalistic as real-world languages do not exhibit such characteristics. While shallow alphabetic writing systems are the most orthographically transparent (i.e., Italian), they are not perfectly transparent and include some minor variations and inconsistencies. Equally, while logographic writing systems are the most orthographically opaque, even the most extreme real-world examples are not perfectly opaque and offer some unreliable indication of sound and/or meaning (i.e., Chinese phonetic and semantic radicals). Further, neither of our artificial languages captured any form of morphology or provided any indication of meaning. While both trained writing systems incorporated semantic representations, neither orthography encoded semantic structure. In fact, an orthographic transparency/morphological complexity trade-off is observed in natural languages (e.g., Finnish is highly transparent but morphologically complex) which reinforces why an artificial alphabetic orthography needs to capture morphology to be considered more naturalistic. Further, while intentional to support efficient learning, our artificial orthographies were far more simplistic than real languages. Phonological forms were all CVC and included only four vowels and eight consonants, alphabetic orthographic forms were each comprised of only three graphemes with 12 in total, logographic orthographic forms were all pictographs with substantial visual overlap, and both languages incorporated just four types of semantic meanings which were all names of animate and inanimate objects. Finally, both artificial languages included only 24 words, considerably less than natural languages. Combined, these intentional compromises limit generalisation of our results to real world language learning.

Future research should focus on addressing the limitations of our simplistic artificial languages. In principle, highly complex artificial orthographies that more closely represent the full range of extant orthographic systems, capturing both phonology and morphology, could be designed with far more words and trained over a substantially longer period. Such an investigation would likely avoid ceiling effects observed in our experiment. For example, on the saying the meaning O-S training task, accuracy was initially higher for the alphabetic writing system and significantly increased over time, but the two writing systems quickly converged. Nevertheless, we cannot know what would be observed if artificial languages contained far more words. The alphabetic orthography could have evidenced higher accuracy throughout training, for even longer should the training period be extended, or perhaps the two writing systems would never converge. Should future research choose to extend the training period, this would also empower our methodology to investigate whether current findings endure over time. For example, the different learning strategies we observed for maximally distinct writing systems may potentially change or mature. Perhaps subtle orthographic effects on spoken language processing would gradually emerge with more deeply embedded knowledge of trained orthographies or the observed impact of writing systems for literacy acquisition may be even more prominent. Equally, such an investigation may find evidence supporting the strategy-shift hypothesis. Mei et al. (2014) found that reading strategy for alphabetic orthographies shifted from assembled (O-P) to addressed (O-S) with continued practice; "*compared to untrained words, trained words in the assembled phonology group showed stronger activation in the addressed phonology network and less activation in the assembled phonology network.*" Finally, creating artificial orthographies that represent the entire spectrum of orthographic transparency would facilitate a more robust comparison to previous work training computational models on the full range of orthographic systems (i.e., Smith et al., 2021), building upon key implications and contributions of our study.

Future research should also explore the implications of bilateral neural activations in greater depth. For example, to investigate a shift from greater activity for alphabetic > logographic to logographic > alphabetic written words along left vOT and the ventral pathway, future work could extend univariate analyses to equivalent ROIs within the right hemisphere. Here, we would expect to only observe such a shift in activity in the left hemisphere which could be supported with greater understand of its presence in the right hemisphere. In addition, future research could consider alternative methods of input coding with regards to prediction dissimilarity matrices for RSA as such decisions may have profound consequences for observed findings, plus our RSA results are somewhat unclear. For example, we coded orthographic dissimilarity as position specific but they could also be coded as position non-specific. Further, we encountered small negative correlations between orthographic and phonological dissimilarity matrices for the logographic writing system as we did not randomly redistribute written words. Instead, we specifically redistributed them to ensure that similar written words did not share sounds. While we can discount any potential implications for interpretation because we did not find any significant correlations for one of the two matrices during analyses within auditory and visual modalities, future work should explore alternative ways to avoid this phenomenon. Finally, we discussed two minor data collection errors during scanning which should be avoided if future work decided to replicate our methods. Nevertheless, we tested potential implications and concluded neither error had any significant impact on our results.

6.6. Conclusions

Overall, this investigation revealed striking differences in the way we learn to read alphabetic and logographic writing systems. Our findings indicated that alphabetic words favour orthography–phonology mappings while logographic words rely more on orthography–semantic mappings. Univariate neuroimaging results indicated that participants learned to read words from different writing systems in different ways; the dorsal pathway (believed to underpin spelling-sound computation) showed greater activity for alphabetic written words; the ventral pathway (including brain regions associated with lexical semantics and whole-word recognition) was more active for logographic words. Equally, RSA revealed that neural representations only encoded the phonemic/orthographic structure of alphabetic written and spoken words. Here, the implication is that sub-word spelling sound information was favoured when reading alphabetic words, while whole-word lexical-semantic information was favoured for the logographic writing system. Nevertheless, our findings consistently did not support the assertion that the orthographic transparency of a writing system impacts on spoken language. Combined, these results advance our understanding of how writing systems impact on reading acquisition and spoken language systems. They suggest that different strategies are used to learn alphabetic and logographic languages and that differences in both the division of labour and nature of neural representations can arise from the orthographic structure of a writing system. Importantly, a comprehensive understanding of the processes involved in reading acquisition and possible consequences for spoken language will help inform best practices for reading instruction across different writing systems, improving levels of global literacy.

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