The Development of Orthographic Knowledge:

A Cognitive Neuroscience Investigation of Reading Skill

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This investigation compared the effects of explicit letter-sound training to holistic word training on the development of word recognition in a novel orthography paradigm. In a between-subjects design, participants were trained to read spoken English words printed in the alphabet script of Korean Hangul. Training took place over four separate sessions with assessment measures conducted throughout. Compared to the holistic training, the component training condition resulted in significantly better transfer to novel word forms and retention of previously learned items. Furthermore, compared to component training, holistic training yielded greater sensitivity to frequency. Variability in the holistically trained condition revealed bimodal distribution of performance: a high and low performing subset. Functional MRI measured cortical responses to the training conditions. Imaging results revealed generally greater responses in the "reading network" overall for the explicit component-based training compared to holistic training, in particular, regions of the inferior and superior parietal gyri as well as the left precentral gyrus. In a comparison of readers within the holistic group, we found that readers who implicitly derived the sublexical patterns in the writing system activated more of the reading network than those who did not sufficiently acquire this knowledge. This latter group primarily activated ventral visual regions. We conclude that explicit training of sublexical components leads to optimal word recognition performance in alphabetic writing systems due to the redundant mechanisms of decoding and specific word form knowledge.

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PREFACE

The work contained in these pages is the culmination of over eight years of blood, sweat, and tears at the University of Pittsburgh. Despite the long tenure and hardships, what I have gained in terms of knowledge, skills, and personal relationships has been invaluable. There are so many people who have made this all possible. While I will save the most important for last, I must first thank my committee. In particular, a large deal of praise and gratitude goes to my thesis advisor Charles Perfetti, who has been a figure of overwhelming support both intellectually and personally. He has been the patron of much of my work in many senses of the word without his backing this study would not have been possible. Many thanks are also due to my co-advisor Walter Schneider, who has provided me with the knowledge and opportunity to study functional magnetic resonance imaging (fMRI) and allowed me to explore this methodology to study skill development in reading. The study contained in these pages is a result of the long hours of collaboration with Dr. Schneider. In addition, large tribute goes to Bruce McCandliss, who gave me my start in fMRI along with Dr. Schneider and is progenitor of the artificial orthography studies upon which this work is based. I also would like to thank the other members of my committee: Julie Fiez, Erik Reichle, and Isabel Beck, all of whom have provided substantial guidance in this thesis and in my development as a scientist and academician.

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In graduate school, I entered feeling that nothing was more important in life than moving up, making new discoveries, and advancing science. That all changed, when I met a little girl named Lauren. With her, my life changed and it continues to especially with my other precious little girl, Kyleigh Rose. I met Lauren and made her my daughter, because I fell in love with the most incredible woman, my wife. My wife continues to change my life and my perspective on the world by her incredible gift of caring, her dedication to the disabled and underprivileged, and her unconditional love for family. No one could be happier to hear that this thesis is finished. Lastly, to the people who have really been there from the start: Mom, Dad, and Christine, words cannot express how grateful I am. I can truly say that I would not be who I am or where I am, if not for you continued love, support, and pride.

1.0 INTRODUCTION

The specific aims of this investigation are to track the cognitive development of word reading and the underlying cortical variations resulting from differential training methods. We discuss in detail the cognitive mechanisms involved in visual word recognition in alphabetic writing systems and how variations in instructional methods result in different learning outcomes. Particularly, we emphasize the comparison of explicitly training the letter-sound correspondences of the writing system contrasted with holistic word form training in which this decoding knowledge must be implicitly derived. We argue that explicit training results in more efficient word learning through internalization of the underlying code whereas holistic training can lead to failures in deriving these sublexical structures. One implication of failing to learn the underlying code is that this results in logographic reading performance similar to that seen in reading disability (phonological dyslexia). Our goal is to track behavioral performance throughout training and to uncover training-related differences in the neural mechanisms that support word recognition. We briefly discuss the cortical structures known as the "reading network" and the different pathways that are hypothesized to support grapheme-phoneme decoding compared to word-form processing (Paulesu et al., 2000). We also discuss similar differences in cortical structures that are believed to account for reading disability (Shaywitz et al., 2002; Pugh et al., 2001) and variations in alphabetic compared to logographic writing systems (Bolger et al., 2005). We then present a cortical framework that accounts for skilled word recognition and how this system develops. Based on this framework, we make specific predictions on the cortical outcomes of our experimental paradigm.

1.1 BACKGROUND

The study of the development of reading ability and disability over the past thirty years has emphasized the necessity to acquire the principles of mapping aspects of the written language system onto the corresponding components of the spoken or oral language system (Perfetti, 2003). Whereas the Universal principle of all writing systems is that they represent visually the fundamental unit of communication, the spoken word (Perfetti, 1994), writing systems vary in the way in which they encode the spoken language and also in the optimal means for developing skilled word recognition. In particular, intensive study of the alphabetic writing system of English has shown that the successful acquisition of spelling-sound correspondences, which, in general, map graphemes (letters) to phonemes (letter sounds), determine reading proficiency and conversely relate to impaired reading ability (Stanovich & Seigel, 1994; Shankweiler et al., 1995).

Evidence that phonics-based training, explicit training of the grapheme-phoneme correspondences of the writing system, yields better transfer, retention, and overall learning rates comes from the extensive literature on reading development and instruction (NRP, 2002). Although there are many studies showing benefits of systematic phonics training (for review, Bus & Ijzendoorn, 1999; Ehri et al., 2001; NRP, 2002), there is limited understanding of the mechanism of this benefit. Alternatively, it has been argued that minimal instructional energy should be spent on explicitly training these letter-sound relationships since the overall goal is the acquisition of a highly developed vocabulary, that is, a visual lexicon (Goodman, 1967; 1996). One of the most recognized models of word reading, the dual-route hypothesis (Coltheart, 1978, 1999), proposes that there are two mechanisms for word recognition: the primary mechanism of addressed phonology in which a stimulus is compared to items in a visual lexicon, and the secondary mechanism of assembled phonology in which a stimulus is decoded via letter-sound correspondence until a phonological word form is generated. Evidence for the primary route or lexical route is that although non-words can be read via a phonological system, exception words by this rule cannot. Exception words like *pint* and *colonel* cannot be readily identified by activating the corresponding phonological representations of the letters or graphemes, because they are not informative actual pronunciation or meaning of the words (Coltheart, 1978). The primacy of the holistic word mechanism of this model suggests that training which is targeted at such a level will result in optimal word recognition performance. *The primary goal of this investigation is to determine whether explicit training in the letter-sound components of an alphabetic writing system, compared to a holistic word-form based training model, will result in more effective and efficient word recognition skills*. In an experiment using a novel orthography, we controlled the feature similarity and practice experience of the learners to identify whether these training methods yield differential learning outcomes and if they rely on unique cortical mechanisms.

Separable cortical mechanisms subserving addressed (lexical lookup) versus assembled (sublexical grapheme-phoneme mapping) processing have been postulated in the literature (Rumsey et al.,1997; Paulesu et al., 2000; Jobard, Crivellor, & Tzourio-Mazoyer, 2003). Specifically, a "ventral" route involving anterior aspects of the left ventral inferior temporal and inferior frontal regions have been suggested as serving as the lexical processing route; whereas a dorsal route involving angular gyrus, the superior posterior temporal region, and the posterior inferior frontal region is considered as the sublexical print-sound processing pathway. *The second goal of this investigation is to understand the cortical mechanisms implicated in explicit component-based compared to holistic word based training methods.* An fMRI component of this experiment measured cortical activity following the behavioral training paradigms to track training-related differences in the network of regions associated with word recognition.

Reading Instruction

The strong relationship between learning to read and the explicit awareness of the segmental structure of the spoken language has been extensively studied since Liberman and his colleagues (1974), receiving ubiquitous support over the past 30 years. The 'phonemic awareness' hypothesis generally posits that if a child cannot segment the units of a syllable into separate sounds, then they will never acquire the 'alphabetic principle,' that is, the fact that letters represent individual sounds in words. The ability to parse and manipulate the phonological units of words is well correlated with literacy skills from word recognition to text comprehension (Bradley & Bryant, 1983, Share & Stanovich, 1995), and the alphabetic principle is thought to be at the foundation of acquiring proficient word reading skill.

Instructional interventions focusing on the relationship between letters and sounds have proven effective for the remediation of reading deficits (Temple et al., 2001; McCandliss Beck, Sandak, & Perfetti, 2003; Shaywitz et al., 2003; 2004). For example, by providing an hour of phonics-based intervention per day for one school year, Foorman (et al., 1997) found significant increases in decoding and word identification skills. In a similar study of children at-risk for academic failure, Foorman (et al., 1998) found that phonics training had a substantial impact on word identification (increase in standard deviation above control group, d=1.63), decoding (d=1.14), spelling (d=0.56) and comprehension (d=0.32). To illustrate one example, a child at the end of the second grade was unable to decode words after two years of normal instruction and one year of reading remediation by the school system. With a targeted reading treatment program that focused attention on visual and phonological segmentation of words (McCandliss et al., 2003), a fifty hour intervention program resulted in a five grade-level advancement in standardized reading test performance. This recent intervention program conducted at the University of Pittsburgh attempted to directly train impaired readers to attend to these consistencies. It was successful in remediating decoding abilities, producing an average of one grade level advancement in less than twenty-four hours of instruction on word recognition and comprehension scores (McCandliss et al, 2003).

But reading development is not solely determined by the level of letter-sound knowledge that is acquired. According to the developmental frameworks of reading that we espouse (see for example Perfetti, 1992; Ehri, 1992; Share, 1995), children begin to utilize letter-sound knowledge as a bootstrapping mechanism in the development of fully specified orthographic "word forms." That is, at the outset of learning, children must acquire sufficient letter-sound knowledge to enable them to decode familiar and novel words in isolation. These isolated decoding events enable the instantiation of a "word form" representation that becomes increasingly specified with each successful exposure to the item. Thus, reading development, even in alphabetic writing systems requires the instantiation of a holistic word form as well as the letter-sound knowledge of which the system is composed. Furthermore, as their knowledge of word forms grows, children's knowledge of spelling-sound correspondences becomes increasingly sophisticated, going from one-to-one mappings of a grapheme to a phoneme (e.g. 'c' to /k/), to one to many mappings (c to /k/ and /s/), eventually learning contingent rules.

Studies have reported that less skilled readers do, in fact, have difficulty with variable consonant sounds such as the hard/soft "c" or "g" (Venezky & Johnson, 1973), and with complex consonants such as '–nt' or '–rst' at the end position of words (McCandliss et al., 2003a; Bolger, Van Dyke, Landi, Perfetti & Foorman, 2002). Difficulty in learning vowels (Fowler et al., 1977), where the mapping between letter and sound is roughly 0.58 (Treiman et al, 1995), supports the expectation that the lack of consistency in the spelling sound correspondence hinders reading acquisition. Thus, differences in reading ability are marked by refinements in the way that print-sound relationships are represented, which are fundamental driven by the ability to access the stored representations of holistic word forms. The development of this coding structure can be implemented as an emergent pattern in a parallel-distributed network (Harm & Seidenberg, 1999; Plaut et al., 1996, Harm, McCandliss, & Seidenberg, 2003).

Several lines of evidence suggest that word forms can be learned in holistic fashion. Reading interventions conducted by Royer et al (1994) suggest that increasing fluency through systematic whole word training results in the strengthening of *reflexive* phonology (Perfetti, 1992), the process of deriving print-sound correspondences implicitly, in struggling readers. Bolger et al. (2002) found that the frequency of repetition of orthographic rime patterns within words embedded in a story significantly predicted performance on isolated novel word and pseudoword reading with items containing those same patterns. Findings from Ehri & Wilce (1985) reveal that pre-readers with limited decoding knowledge perform well on learning visual forms which have arbitrary relationships with paired phonological words (e.g. "qDjK" for the word "scissors"). However, several studies using manipulated orthographies have uncovered the limitations of deriving letter-sound correspondences from whole words. For instance, Byrne and colleagues (Byrne, 1992; Byrne & Carroll, 1989) have shown that learners, particularly preliterate children, when confronted with the task of associating linguistic forms with graphic symbols will tend to map forms at the lexical and not the sublexical level. Thus, whole word training can in some instances provide the environment to acquire sublexical letter-sound knowledge; however, the effectiveness of this learning may be limited to particular levels of reading skill.

Reading Skill & Disability

Based on the evidence from studies of skill development, preliterate and low skilled children have greater difficulty parsing the speech stream into individual phonemes which enable the letter-sound relationships to be acquired (Ehri & Wilce, 1985; Ehri, 1992; Liberman et al., 1967) and thus these readers tend to reflect more holistic knowledge of word forms (Ehri, 1992; Adams, 1990). Impairments in reading disability have also been shown to reflect differences in the ability to acquire letter-sound relationships or the ability to store holistic representations of lexical items. The more common form of reading disability is *developmental* or *phonological dyslexia*, which is characterized by failure to read pronounceable pseudowords and low frequency words via letter-sound decoding, but maintain some ability to read high frequency words. The less common form of disability is *surface alexia,* which is characterized by impaired ability to read irregular/exception words that do not follow standard letter-sound correspondences, but retain the ability to read 'regular' words that follow consistent letter-sound mappings (Castles & Coltheart, 1996). The assumption here for the dual route models is that the direct lexical route is damaged, thus leading to over-reliance on the grapheme-phoneme correspondence of the non-lexical route. Whereas in the case of phonological dyslexia, it is the sub-lexical (letter-sound knowledge) route that is impaired causing a reliance on the holistic, lexical route. This phonological form of the disability is argued to stem from a failure to "develop" the ability to parse the speech stream and sufficiently acquire the decoding knowledge (Lieberman et al., 1990). As we discussed earlier, explicit instruction of decoding knowledge enables the remediation of deficits in word and non-word reading (McCandliss et al., 2003a). Thus, it may be argued that this developmental form of reading disability may come from failures in instruction methods to adequately address explicit grapheme-phoneme relationships (Adams, 1990; Beck, 2005).

A fundamental question that we address in this study is whether training in a holistic fashion produces the deficiencies seen in developmental dyslexia: failure to read low frequency and novel words and to decode pronounceable non-words. Thus, the effects of holistic training may result in a variety of learning outcomes. In the optimal case, learners may implicitly derive the sublexical knowledge necessary for decoding words similarly to those trained explicitly on the pattern. In the less optimal case, learners insufficiently derive sublexical knowledge resulting in generally poor learning and performance on decoding word forms. And in the extreme case, learners may acquire no sublexical knowledge resulting in logographic type reading patterns in which no ability to decode is evident—we will expand on this hypothesis later.

Training Paradigms

Several paradigms have been devised using artificial or novel orthographies to test the differential effects of component and holistic training on acquiring knowledge (Bishop, 1964; Jeffery & Samuels, 1967; Byrne & Carroll, 1989; McCandliss, Schneider, & Smith, 1997). These investigations vary along several dimension including the age of participants, (from pre-literate children to adults), orthography used (natural orthographies such as Arabic to artificial graphs), and training stimuli (pseudowords, words, etc.). In all but one instance (Xue et al., in press), the authors compared some form of component-based learning to a holistic word learning condition. For instance, Bishop (1964) conducted one of the earliest novel orthography studies training adult subject to read words in Arabic script. The findings of his study revealed that letter training compared to whole word training lead to better transfer performance to reading novel words. However, the holistic condition faired better than the untrained control group at this task suggesting that these learners were picking up on some of the regularities in the letter-sound pattern even if they could not explicitly state them. Jeffrey & Samuels (1967) conducted a similar study using an artificial script on pre-literate children to test if they had the capacity for analytic phonology, the decomposition of letter-sound relationships from whole word experiences. They also found that explicit training on the letters of this script lead to better transfer to novel word items (using only 2-phoneme word stimuli such as, /m/ + /ay/) than the holistic group, but unlike Bishop's (1964) work, the holistic group did not outperform the untrained control group. Byrne and colleagues (Byrne, 1992; Byrne & Carroll, 1989; Byrne & Fielding-Barnsley (1989) conducted a series of studies with pre-literate children using geometric patterns and colors that were associated with a) whole lexical items in two word phrases, b) syllable units in di-syllabic words, and c) individual phonemes in pseudowords. They found that preliterate children could map symbols to whole word items (Byrne, 1992) and could map symbols to syllables (Byrne & Fielding-Barnsley, 1989), but they were completely incapable of mapping symbols to individual phonemes (both studies). These findings suggest that phonemic awareness is a result of, not a precursor to, literacy training (Byrne, 1992).

In a more recent study, Bitan & Karni (2003) trained adults to read words using a morse-like script in which multiple symbols corresponded to a single letter. They manipulated three training conditions within-subject: a) explicit training of letter-sound correspondences, b) implicit training on holistic words, and c) an arbitrary mapping condition to mimic logographic reading. The results of this study found that the acquisition of letter-sound components of the language only occurred when participants were exposed to the code explicitly prior to implicit (holistic) training. Thus, the performance on transferring the letter-sound knowledge to reading new words only occurred for the explicitly trained group. On the other hand, they found that explicit training did not transfer to learning words in a completely novel orthographic system; whereas implicit and arbitrary training conditions transferred well to these novel situations. Bitan & Karni (2003) found that these training conditions generally did not differ in learning rate in terms of retention and conclude that the same basic learning mechanisms subserve the acquisition of the lexical knowledge for these systems, but that a unique mechanism subserves decoding knowledge of letter-sound relationships.

The investigation reported here is based largely on a paradigm developed by Bruce McCandliss (McCandliss, Schneider, & Smith, 1997) in which adults were trained to read words in an artificial script via a component phonics-based as compared to a holistic method. In the original study, participants were tested and trained on a new set of words in 4 separate sessions allowing for the measurement of transfer and retention across time. As opposed to Bitan & Karni (2003), the results of this study showed differential learning curves for the holistic compared to component group. McCandliss et al. (1997) found that despite the high degree of within-session learning for the holistic group, these subjects showed poor retention of knowledge from session-to-session and poor overall transfer of knowledge to novel items. In contrast, the component group showed a slower overall learning curve with a high rate of retention and positive transfer to novel items. After the completion of the 4 sessions, subjects were asked to report their knowledge of the letter-sound code. Like Bitan & Karni's (2003) stimuli, the stacked vertical grapheme units used in McCandliss et al's (1997) study were difficult to visually segment without explicitly highlighting the visual components. Subjects in the holistic condition failed to produce any of the visual components nor could they associate the proper phonemes with any semblance of a visual letter; whereas the component group performed at ceiling for the task. The complete lack of awareness of an underlying code suggests that the McCandliss paradigm was successful at creating a logographic compared to alphabetic training environments. Thus, we chose to replicate this basic paradigm in our own investigation in order to test the differential effects of training in alphabetic systems on word recognition and the underlying cortical network.

Summary

We hypothesize that skilled reading in an alphabetic writing system requires that the learner a) acquire the set of individual orthographic units that make up the system, b) be able to isolate the units of speech corresponding to these orthographic units, c) systematically map the orthographic and phonological units in the context of words, and d) acquire *holistic* word-specific representations of the items encountered. Second, optimizing word recognition skill requires that each of the sub-skills listed above can be achieved with a level of automaticity that enables fast and accurate recognition of familiar items as well as transfer of skill to novel word items (and pronounceable pseudowords). The determining factor of both skilled word reading and reading impairment is the fluency that is achieved in recognition of items *holistically* and *decoding* of unfamiliar items (Zeigler et al., 2003; Stanovich & Seigel, 1994). Thus, we further hypothesize that instructional methods for reading in alphabetic systems which ignore the grapheme-phoneme components of the writing system will fail to develop the decoding sub-skills necessary to read novel and pseudowords. However, the subsequent ability to implicitly derive the letter-sound patterns from identifying words fluently relying on quality holistic word forms (*reflexive* phonology, Perfetti, 1992) is hypothesized to be critical to the development of skill as well. Therefore, an important component to this inquiry is to understand the effects of explicit instruction of components of the alphabetic writing system as compared with holistic training without this explicit component knowledge.

The implications of these assumptions are that, when training of the mapping principles in an alphabetic system are explicit, the knowledge is internalized, enabling the reader to better retain knowledge of the word forms encountered and to transfer this knowledge to novel words. In contrast, training an alphabetic system in an holistic manner is likened to a logographic writing system in that, unless the components are implicitly derived, the mapping principles will not be internalized, resulting in poor retention of word knowledge and an inability to transfer this knowledge to novel forms. *The third goal of this investigation is to test whether direct training of the mapping principles of a writing system result in better retention and transfer than more holistic lexical training, and whether this latter training can result in logographic type reading in written word forms are mapped to their lexical, but not sublexical constituents.*

1.2 COMPARING ALPHABETIC AND LOGOGRAPHIC WRITING SYSTEMS

Does learning to read in an alphabetic system invoke a fundamentally different set of cognitive processes and underlying neurological mechanisms than learning to read in a logographic system? *The fourth goal of this investigation is to determine whether holistic processing of alphabetic writing systems can result in logographic reading and determine variations in cortical activation underlying alphabetic compared to logographic reading.* Examining the cortical processing of writing systems across languages, affords us the opportunity to compare whether alphabetic and logographic systems rely on a common set of neural regions or on distinct specialized regions emphasizing the unique mappings to phonology and lexicosemantics.

Different writing systems represent the spoken language in very different ways. Alphabetic writing, which, in its visual form, encodes spoken units at the level of the phoneme, does vary in how consistently it maps graphemes to phonemes, with "shallow" orthographies, such as Italian and Finnish, having more consistent mappings than the "deep" orthography of English, and its notorious irregularities. But even the deepest alphabetic orthography maps graphemes to phonemes. By contrast, the writing system in Chinese is often characterized as logographic, assuming each character maps to a spoken word, or ideographic, assuming each character corresponds to semantic representation; however, closer scrutiny of the orthography reveals that graphemic units known as radicals encode information about pronunciation, semantics, or both (for an in-depth account of Chinese word processing see Tan et al., 2005). Although, in principle, one could read Chinese directly for meaning without using pronunciation, the behavioral research on reading suggests that Chinese reading, like alphabetic reading, involves phonology as well as meaning (Perfetti et al, 2005). The reason for this is that the character is connected to a syllable pronunciation as well as to a meaning, leading to the activation of a spoken syllable when a character is read. In the case of Japanese, two writing systems have been developed: katakana (or Kana), in which a single grapheme corresponds directly to a spoken syllable, and katakanji (or Kanji) in which a single grapheme corresponds to a morpho-semantic unit. Despite the strong association between visual and semantic codes, the output of the Chinese and katakanji writing systems, as all writing systems, ideally reflect the spoken forms of words (Perfetti, 2004).

English, Japanese (Kana), and Chinese writing systems differentially map onto phonological and semantic aspects of language. However, does this differential mapping result in variations in cortical specialization for writing systems? From the standpoint that writing systems share a universal principle, specifically that all writing systems encode spoken word forms, we would predict that all writing systems rely upon a common network of cortical regions which map visual forms to spoken word forms. However, because writing systems differ with respect to how the encode spoken language (i.e. at the level of the phoneme, syllable, or morphology/lexical in the present cases), we predict that cortical activation differences between writing systems (beyond the basic visual features) are due to these differences in how the spoken language is encoded/decoded from the visual form.

Reading in a logographic system like Chinese or Japanese Kanji requires a set of principles mapping print to speech that differ dramatically from alphabetic writing systems like English and Korean. In the former case, the printed forms or graphs readily map on to structures of meaning and the phonological word forms, which are single syllables. While there are caveats—compound forms in Chinese can have components (radicals) for which the sole purpose is pronunciation—the general structure of the mapping system between print and sound is at the level of the word form. On the other hand, the visual graphs in alphabetic writing systems represent speech sounds at the level of the individual phoneme, and to establish a word form representation it is necessary to be able to decode the letter-sound principles of the language. The differences in mapping principles between these two writing systems have implications for the way in which words are learned, that is, in order to learn a new visual word form in a logographic system one must see the graphic unit paired with the spoken word form (assuming the meaning of the phonological word form is already known). Thus, the learning task is essentially a paired-associate process requiring repeated pairings in order to establish the print-sound relationship between the written and spoken word. Optimal learning in alphabetic systems requires that the reader learn that the printed code underlying word processing reflects individual phonemes. Therefore, identifying written words does not necessarily require constant paired exposure with the phonological form, rather by learning the relatively limited number of letter-sound principles a learner can decode almost any lexical item in the language. In sum, learning to read in logographic systems requires pairings of visual and phonological word forms and the knowledge of prior forms will not aid in the learning of future forms; whereas in alphabetic systems learning to understand the letter-sound code within words enables the underlying decoding principles to be acquired allowing for unknown written word forms to be easily decoded and acquired. Greater experience with decoding known words allows for better acquisition of the underlying code and thus enables better decoding of unknown word forms. Moreover, because the underlying code is being learned as well as the word form fewer exposures to the spoken word are required to establish a quality representation of the word form which leads to better retention. To summarize, compared to logographic systems, alphabetic systems lead to faster learning, better retention, and transfer or generalizability across items in the system.

1.3 CORTICAL MECHANISM OF READING

The study of reading is well represented in the neuroimaging literature with over 150 scientific articles covering visual word recognition in skilled and impaired adults and children (see for reviews: Bolger, Perfetti, & Schneider, 2005; Fiez & Petersen, 1998; Jobard, Crivello, &

Tzourio-Moyer, 2003). The process of deriving a neuro-anatomical model of the reading process has developed over the past decade revealing a reliable set of cortical regions associated with orthographic, phonological and lexical/semantic processing (Fiez & Petersen, 1998; Price, 2000; Jobard et al., 2003; Bolger et al., 2005) and models of cortical development are beginning to emerge (Pugh et al., 2001; McCandliss et al., 2003). A vast number of early studies set out to disambiguate the cortical mechanisms underlying the cognitive components necessary for word identification (*i.e*., orthography, phonology, and lexicon). A comprehensive study by Pugh et al. (1996) laid the initial groundwork in identifying the cerebral organization of word identification processes using fMRI techniques. They used a complex methodology of subtraction in order to single out the active neural structures corresponding to the particular cognitive functions being performed (previously listed above). The Pugh study identified broad regions in the left prefrontal cortex associated with lexico-semantic processing using a categorization task. Regions in the superior and medial temporal gyrus were active in both rhyme and semantic tasks while extrastriate regions in the ventral visual cortex were active during the orthographic tasks.

There is general agreement as well as quantitative evidence across studies (Bolger et al., 2005) for a specific network of regions associated with visual word recognition. To reiterate, the general cortical network for word reading includes the left ventral occipito-temporal region, the left superior posterior temporal region, the left parietal lobe (superior and inferior aspects), and the left inferior frontal region (from superior posterior to ventral inferior aspect). These broad regions are characterized by the particular functions that they are believed to subserve. We will briefly discuss the structure-function relationships for the anterior aspects of this network which are associated with both spoken and written language (Price, 2000) then discuss a more detailed framework for the left occipito-temporal region associated with visual orthographic processing.

Several studies have focused on the multi-faceted role that the superior temporal gyrus region plays in spoken language (Simos et al., 2000; Price, 2000), reading (Temple, 2002; Temple et al., 2003; Booth et al., 2003) and verbal working memory (Paulesu et al., 1993; Chein et al., 2002; Ravizza et al., 2004). Many of these studies suggest a distinction between the more posterior temporo-parietal boundary region (including angular and supramarginal gyyi) involved in phonological analysis and grapho-phoneme conversion (Booth et al., 2003; Temple et al., 2003), and a more anterior perisylvian region (Heschl's gyrus and Planum Temporale) that is involved in more complex aspects of speech comprehension. In their meta-analysis, Tan et al. (2005) found activation and greater convergence in the dorsal extent of the inferior parietal lobe (BA 40) for Chinese than for English/alphabetic studies, but the converse is true in the ventral aspect of this region. Thus, the superior posterior temporal/inferior parietal region may show functional distinctions according to alphabetic and logographic learning.

A meta-analysis of verbal working memory tasks performed by Chein et al. (2002), found functional heterogeneity in the left inferior frontal region of cortex. More specifically, they found that the more superior posterior aspect of inferior frontal gyrus is associated with level of difficulty (e.g. load manipulations), whereas the anterior *ventral* aspect of inferior frontal gyrus was associated with contrasts of words and pseudowords. This finding is consistent with that of Poldrack et al. (1999) which found that the superior posterior aspect of inferior frontal gyrus is involved in phonological processing, whereas the ventral anterior region is engaged in more semantic processing. The inferior frontal region has also been implicated in terms of skill differences (Shaywitz et al., 2003) and manipulations of word frequency (Fiez et al., 1999). Whereas the superior posterior region of IFG has been implicated for all writing systems (Bolger et al., 2005), activation spreading from this region to the anterior lateral portion of middle frontal gyrus is consistently found for Chinese, but not Japanese or English word reading (Bolger et al., 2005; Tan et al., 2005) leading to the suggestion of this region's involvement with cross-modal integration of lexical information.

Just as the set of cognitive components are assumed to work interactively to enable successful word recognition, the cortical mechanism underlying these components are also believed to interact in a set of cortical pathways similar to the functional "routes." A study by Judith Rumsey and colleagues (1997) identified similar regions associated with phonological and orthographic processing components of word reading by investigation the frequency by regularity interaction. That is, they factorally manipulated words of high and low frequency with consistent and inconsistent letter-sound correspondences. This interaction is the basis for the notion of two mechanisms for word recognition (addressed vs. assembled phonology) since, compared to high frequency words, low frequency items tend to be read slower unless they follow consistent spelling patterns. Thus, the frequency effects support the primacy of the holistic addressed mechanism, and the interacting role of consistency supports the use of a second sublexical mechanism of assembled phonology (Coltheart, 1978, 1999). Using the dual-route model as the framework for their predictions, Rumsey et al. (1997) concluded that the lingual/fusiform gyri in the visual cortex was responsible for holistic/visual word identification, whereas the posterior superior-temporal gyrus and adjacent posterior temporo-parietal boundary were responsible for more phonological recoding (or grapheme to phoneme mapping) in reading.

Cortical Pathways & Reading Disability

The earliest evidence for the neural basis of reading disability comes from Dejerine (1891, 1892) who described patients with impairments in both reading (alexia) and writing (agraphia). These deficits were associated primarily with lesions to left angular/supramarginal gyrus leading to the suggestion that this area was responsible for the storage and retrieval of visual word forms. However, the syndrome of 'pure alexia' (alexia without agraphia) was associated with lesions to the left ventral visual processing stream or between this region and the angular gyrus (Dejerine, 1892). More specifically, white matter deficits between left posterior occipito-temporal cortex and left angular gyrus produce disconnections between visual and linguistic representations. Dejerine reasoned that angular gyrus in conjunction with Wernicke's area (Wernicke, 1874) comprised a network of associating visual word with spoken word forms respectively. The evolution of models of pure alexia have posited a more central role to the ventral posterior temporal region as an abstract word form processor, and thus named the "VWFA" (Warrington & Shallice, 1980; Geschwind, 1970). Lesions to the VWFA region have resulted in impairments in recognizing and naming words and pronounceable nonwords, but are relatively spared in the identification of digits, objects, and, in some cases, letters themselves; thus suggesting a more abstract computations for candidate word forms (McCarthy & Warrington, 1990; Miozzo & Caramazza, 1998).

Two further subtypes of alexia have since been posited (Kay & Patterson, 1982, Castles & Coltheart, 1996). *Surface alexia* is characterized by impaired ability to read irregular/exception words that do not follow standard letter-sound correspondences, but retain the ability to read 'regular' words that follow consistent letter-sound mappings. This surface form deficit is allegedly localized in the left posterior temporal region disconnected from anterior regions of ventral temporal cortex (McCarthy & Warrington, 1990). *Phonological alexia* is characterized by failure to read pronounceable pseudowords and low frequency words via letter-sound decoding, but maintain some ability to read high frequency words. This phonological deficit is thought to arise from deficits to the left angular gyrus and the superior posterior temporo-parietal junction affiliated with computing print-sound correspondences (Black & Behrmann, 1994). The structural dissociation has lead to the notion of two processing routes in the brain: a dorsal route reflecting the computation of sublexical print-sound correspondences, and a ventral route representing holistic lexical/semantic information (Henderson, 1986; Rumsey et al., 1996).

Evidence from neuroimaging studies have reported that dyslexics fail to engage posterior aspects of cortex that account for the visual and auditory perception involved in word reading (Shaywitz et al., 2001; Pugh et al., 2002). Importantly, many studies have revealed deficits in the temporo-parietal region encompassing superior posterior temporal gyrus (SPTG), inferior parietal lobule (and sulcus), angular and supramarginal gyri (Paulesu et al., 1996; Brunswick et al., 1999; Horowitz et al., 1998; Pugh et al., 2000; Shaywitz et al., 1998). As discussed earlier, structural connectivity of white matter fiber tracts has been shown to be deficient in poor versus skilled readers (Klingberg et al., 2000). Studies correlating activity of the angular gyrus to frontal and ventral fusiform regions of the reading network reveal strong functional connectivity between these regions for healthy but not impaired readers (Horowitz et al., 1998). Pugh et al (2001) conducted their own functional connectivity study of the angular gyrus, which revealed that, in disabled readers, connectivity is weak for word and pseudoword reading, but not for purely phonological or purely orthographic tasks. These findings further suggest that the angular gyrus is the gateway to 'phonological assembly' or mapping orthographic to phonological forms sublexically, whereas the ventral inferior temporal region is the gateway to 'word-form' processing (Perfetti & Bolger, 2004).

Development of Word Recognition Skill in Cortex

While there has been a recent surge in neurobiological studies of the development of reading (Turkeltaub et al., 2003; Shaywitz et al., 2002; 2003), as of yet there is no generally accepted theory of how cortex develops with skill. Imaging studies of reading intervention programs that highlight spelling-sound relationships (McCandliss et al., 1999 reported in Casey et al., 2001; Temple et al., 2003; Small, Flores, & Noll, 1998) find training related increases in posterior temporo-parietal regions associated with phonological processing as well as left occipito-temporal regions associated with orthographic processing. *Thus, in addition to the development of cognitive skill, a goal of this investigation is to understand the developmental trajectory of the cortical reading network, particularly the ventral visual pathway for word recognition.* Our aim is to measure the plasticity of particular regions associated with visual word recognition along as a function of reading skill and frequency of exposure to trained items.

This investigation critically focuses on a well-studied region of the left posterior temporal cortex known as the *visual word form area (VWFA).* McCandliss, Cohen, & Dehaene (2003) proposed that the VWFA "constitutes a special case of perceptual expertise" and that "extensive visual experience with a class of stimuli drives enhancement of perceptual mechanisms and changes in the supporting functional architecture in the left fusiform gyrus" (p. 296).

The underlying framework we propose in this investigation hypothesizes that visual/orthographic processing of written language in cortex is hierarchically organized as a set of perceptual processing components in the ventral visual system. We argue that much of the ventral visual processing stream is well equipped for invariant recognition processes at the level of foveal acuity, and thus the emergence of visual word expertise is subject to the same competition for neural tissue within this region as any other class of objects. We specifically hypothesize that there are distinct regions along the occipital-temporal processing stream that are responsible for orthographic processing, starting with early medial visual regions (V1/V2) sensitive to any visual input; a posterior region on the occipito-temporal boundary (roughly V4: BA 18,19) specialized for the feature-based perception of abstract orthographic units (graphemes—letters in English); a mid fusiform/IT region (VWFA: BA 37) specialized for abstract processing of orthographic word forms; and, an anterior region of fusiform/IT gyrus extending into middle temporal gyrus and the temporal pole (BA 37/21). A similar posterior-to-anterior hypothesis within ventral temporal cortex has been identified by Cohen (et al., 2002) in a review of 25 neuroimaging studies of word reading, and has been subsequently specified in recent work (McCandliss et al., 2003; Dehaene et al., 2005). They report that activation in the anterior region (y = -43, [range -54 – -32]) is responsive to verbal stimuli in visual and non-visual tasks; all associated with semantic vs. non-semantic comparisons. They report that contrasts of alphabetic strings with non-alphabetic stimuli (e.g. false fonts, fixation, checkerboards, etc.) are localized in a significantly more posterior region (y = -60 [-43 – -70]). Cohen et al. (2002, 2000) refer to this posterior region, located in the mid-fusiform (not to be confused with the posterior fusiform, which is part of the lateral occipital region) as the VWFA. The authors identify the more posterior region of fusiform (V4; y < -72) as a general perceptual region specialized in recognizing complex patterns and shapes, but not specifically for orthography. This last region is consistent with the lateral occipital complex (Grill-Spector & Malach, 2001) which is responsive to complex visual patterns (letterstrings, digit strings, and visual objects) but not responsive to abstraction or individuation of these patterns such as transposition (Grill-Spector & Malach, 2001), case change (Cohen et al., 2002), etc.

The framework proposed above dictates that early/posterior regions (V4 bilaterally) should engage early in the process of learning to read words due to a lack of specificity for visual stimuli—for example, this region is engaged in false font tasks. However, findings from several studies of reading skill (Poldrack et al., 1999, 2000) suggest that as skill increases so does lateralization to the left. This is also suggested by the McCandliss et al (2003) framework in which word/letterstring processing becomes increasingly left lateralized at the V4 level. The sum of these findings suggests that the VWFA is late developing and strongly associated with skill development (see for example Shaywitz et al., 2003). As part of this investigation, we tested the predictions of this developmental framework. Employing a novel orthography training paradigm, in combination with fMRI, we attempt to identify training-related effects in the reading network, and in particular, the left ventral pathway.

Cortical Variations across Writing Systems

In a neuroimaging study comparing more and less transparent alphabetic orthographies which are thought to rely differentially on lexical/addressed versus sublexical/assembled mechanisms, Paulesu and colleagues (2001) found that the more transparent orthography of Italian relied more heavily on the dorsal pathway of the superior posterior temporal region compared to the less transparent English orthography which relied more on the ventral pathway of the VWFA and inferior frontal gyrus. Neuroimaging investigations of non-alphabetic writing systems suggest that separate processing pathways exist for different systems. For example, studies of Japanese Kana and Kanji processing have enabled a within-subject, within-language comparison of two writing systems with differential mapping properties. In the katakana (or Kana), a single grapheme corresponds to a spoken syllable; the kana are combined to produce multi-syllabic words. The katakanji (or Kanji) system, borrowed from Chinese, uses characters that correspond directly to words, pronounced either in Japanese or in Chinese. Several neuroimaging studies of Japanese reading reveal differential processing routes for Kana and Kanji processing (Sakurai et al., 1994; Hamasaki et al., 1995). Similar to studies of English reading, Japanese researchers have postulated a ventral route that maps graphemic forms to lexical-semantic information for the processing of Kanji (logographic) and a dorsal route for the processing of Kana (syllabo-graphic) (Nakamura et al., 2002).

The study of Chinese reading in neuroimaging has often revealed idiosyncrasies from other writing systems, particularly in the visual processing system. For example, Tan et al. (2000) found right-lateralized occipital activation in processing simple and complex Chinese characters. On the other hand, others found generally similar patterns of activation in Chinese and English reading in bilingual subjects (Chee et al., 1999) and similar activation patterns have been found for Chinese character and pinyin (an alphabetic system for Chinese commonly used in early childhood) reading (Fu et al., 2002). However, Perfetti & Liu (2005) have shown that cortical activity in learning to read in a second language is often largely determined by the primary language. Recently, studies of Chinese reading have focused on the left dorso-lateral frontal region (Siok et al., 2003; 2004). According to Tan et al. (2005), this region is unique to Chinese reading and strongly predicts reading ability in Chinese (Siok et al., 2004).

As we noted above, English, Japanese (Kana), and Chinese have developed different levels of mapping to the phonological and meaning components of language. From the standpoint that writing systems share a universal principle—all writing systems encode spoken word forms—one expects a common network of cortical regions which map visual forms to spoken word forms to emerge from convergent evidence. From the standpoint of the different levels of mapping used by writing systems, one expects some accommodation of this universal network to specific differences   At the core of this universal network, based upon the findings of Jobard et al. (2003), lies a visual word form system responsible for recognizing the graphic forms of words and relaying that information on to those regions central to phonological and lexical/semantic processing. Regions unique to each language will reflect the language-specific nature of phonological and semantic decoding (Bolger et al., 2005; Tan et al, 2005).

In a meta-analysis of neuroimaging findings for word recognition across writing systems as diverse as Chinese characters, Japanese Kana, and the English alphabet, we (Bolger et al., 2005) found a predictable network of regions associated with reading is well-replicated across languages and writing systems. Despite the variability in mapping between orthography and phonology and between orthography and lexical/semantics, the results suggest that writing systems activate a strong network of common regions including: a) the left occipito-temporal region, b) the left superior posterior temporal and inferior parietal region, and c) the inferior frontal region . The meta-analysis conducted for studies of Kana and Kanji reading revealed that regions recruited for processing the individual writing systems with their unique mappings are in large part common to both writing systems. Similarly, the meta-analysis of Chinese character reading when overlaid with Japanese and English writing systems again revealed more regions that are common across than distinct to individual writing systems. In particular we found that the region of the left mid-fusiform gyrus which has been identified as the target visual word form processor and labeled the visual word form area (hereafter VWFA; Cohen et al., 2000; 2002; McCandliss et al., 2003) is highly consistent across languages and writing systems. Based on a series of findings, McCandliss et al (2003) characterized this region as performing abstract, pre-lexical computations, and Perfetti & Bolger (2004) referred to as a "gateway" region to lexico-semantic and phonological processing.

This study also revealed several regions of divergence across writing systems in the following regions: 1) superior temporal gyrus (posterior aspect), 2) left anterior dorsal frontal region, and 3) right occipito-temporal cortex (inferior occipital and posterior fusiform). For instance the meta-analysis did reveal English and Japanese Kana-specific activations in the left superior posterior temporal gyrus that were more extensive (from medial posterior to lateral anterior aspects) consistent with the idea of a more dorsal processing route; however, there was focal activity in anterior aspects of this region (BA 22) for Kanji and Chinese as well. This study confirmed the notion that Chinese character reading elicits stronger activation in bilateral striate and extrastriate regions, and the role of the left middle frontal gyrus in Chinese word processing. Thus, the findings of Bolger et al (2005) exhibit a network of regions common to reading across languages, and also identify divergences likely reflecting the variations of how the spoken language is specifically mapped to the written language. *A final goal of this study is to potentially determine the source of these convergent and divergent regions by providing evidence from direct manipulations of the two most orthogonal mapping principles, alphabetic and logographic (or lexicographic).*

To summarize, the primary goal of this study is to determine whether explicit training of sublexical letter-sound components compared to holistic lexical training in an alphabetic writing system result in differences in word recognition skill. The second goal of this investigation is to track cortical variations due to these variations in training. Particularly, we set out to test directly whether the dorsal extent of the reading network reflects processing of the sub-lexical components, namely grapheme-phoneme correspondences, and the ventral aspect reflects the lexical processing prescribed for all writing systems. Lastly, we investigated whether holistic or lexical training results in logographic processing of visual word forms in terms of behavioral performance and underlying cortical mechanism. Regions associated with the "logographic" processing of Chinese, such as the right occipito-temporal system and middle frontal region are responding to the putative holistic nature of word processing in Chinese reading. In this endeavor, we seek not only to understand the process of acquiring orthographic knowledge as a function of explicit alphabetic training as compared to a holistic logographic training, but also to understand the cortical outcome measures of the variations in mapping principles.

2.0 NOVEL ORTHOGRAPHY TRAINING STUDY: COMPARING THE EFFECTS OF COMPONENT AND HOLISTIC LEARNING

In the sole study of this investigation, we compare the effects of training of two methods of word recognition in a novel (alphabetic) orthography paradigm: a) a component or phonics-based method in which participants are trained explicitly on the letter-sound patterns within the context of a whole word item, and b) a holistic or logographic method in which participants are not made aware of the component forms explicitly.

The primary goal of the behavioral measures of the experiment is to determine whether component training, compared to holistic training, will result in more efficient word learning. We hypothesize that the explicit nature of the component training enables the internalization of the letter-sound code leads to greater ability to transfer knowledge to novel word stimuli and pseudowords, leads to the establishment of more high quality lexical representations as measured by retention and reading speed, and a lack of sensitivity to word frequency. Thus, we predict that compared to holistic training, the component training group will result in greater accuracy and response time on transfer tasks (novel words and pseudowords) and tasks of retention. Because component training results in more effortful decoding of each letter of a word, holistic learning should be more efficient at the outset. However, as the decoding knowledge becomes internalized and automatic the component training should become more efficient as learners use *redundant* mechanisms of decoding knowledge with more *specified* lexical word form knowledge (Perfetti, 1992). We predict that holistic training will result in initially faster performance than component training but that after several sessions the component training will result in not only more accurate, but overall faster performance.

The second goal of this training paradigm is to test whether holistic training enables the implicit decoding of the letter-sound principles of the writing system or if the underlying code will fail to be acquired leading to more logographic type word learning. Training words in an alphabetic system holistically is not synonymous with logographic writing systems which have no componential graphic-phonological relationship. As we stated above, even Chinese is not a true logographic system because there are component radicals that cue phonological word forms. However, this paradigm attempts to produce logographic word recognition in an alphabetic writing system since it is our contention that holistic training without awareness of the components leads to logographic-type performance outcomes. Thus, we have two competing hypotheses: a) letter-sound correspondences can be derived implicitly in holistic training as demonstrated by Bitan & Karni (2003), or b) holistic training yields logographic word learning in which the letter-sound code cannot be derived as demonstrated by McCandliss et al. (1997).

Based on the findings of McCandliss et al. (1997), holistic-based training, in which learners have limited knowledge of component forms beyond visual patterns (i.e. no relation to sublexical phonological forms) leads to poor retention of word form knowledge and almost zero transfer of prior knowledge to novel word forms. Learners in this holistic method report having learned the word items through pure lexical association, linking the phonological word with the whole visual pattern. The visual forms used in the McCandliss et al. (1997) study were almost impossible to parse without explicit awareness of these component forms; a drastic difference in comparison to naturally occurring writing systems. However, in the study by Bitan & Karni

(2003), they trained participants in a within-subject design to learn words in an explicit component, implicit holistic, and arbitrary mapping conditions and found that the implicit group performed similarly to the explicit group in terms of overall transfer and retention. Whereas the McCandliss orthography was vertically based and difficult to parse, the Bitan & Karni script was linear in nature and not as visually difficult to individuate "letter" forms.

In order to address this issue, we adapted the McCandliss paradigm using a natural alphabetic orthography, Korean Hangul, which is easy to parse yet has dramatically different spatial characteristics than the Roman alphabet (see Figure 2). Since most native English speakers remain largely unaware of the variations in Eastern Asian writing systems, they can not distinguish between Chinese characters, Japanese katakana, and Korean Hangul and the fact that each of these systems represents the spoken language in very unique ways. Based on the sample of subjects used in this study, we inquired about their knowledge of Korean orthography and found that not one of our thirty subjects were aware that Korean was an alphabetic system. Participants assumed, as do much of the population at large, that the Hangul system is logographic as Japanese Kanji and Chinese based largely on the phenomena of the square-like spatial arrangement of the stroke patterns. Thus, Korean was used in this study because of this logographic bias in naïve speakers of English.

The details of our study are largely adapted from the McCandliss paradigm. Participants were trained on a new set of words each session for four individual sessions and tested 3 times per session (beginning, middle, and end) to assess transfer and retention. We used a completely transparent orthography (1-1 grapheme-phoneme correspondence) with 12 letters (8 consonants and 4 vowels) to create 80 CVC structured training words (McCandliss et al. only trained on 64 words). Unlike McCandliss et al., we manipulated the frequency of trained items by exposing half of the words from each session in each of the following sessions such that high frequency words were trained 4, 3, and 2 times more than low frequency words. We assessed learning via a production procedure, in which subjects were asked to read aloud an isolated word, and a recognition procedure, in which subjects were asked to choose the visual word stimulus that matched an auditory cue. Prior to the scanning session subjects were assessed on the identification of novel words and the decoding of pseudowords. Participants were than scanned in an fMRI blocked-design where they were asked to perform a 1-back recognition task on a variety of stimulus conditions in the native (English) and novel (Hangul) orthographies. Participants were then given a grapheme-phoneme production task in the exit interview and probed to describe the strategies used during training.

The goal of our design was to test the hypotheses we discussed regarding the cognitive and behavioral outcomes, and to subsequently identify cortical mechanisms that differentiate between training conditions. The secondary question was whether we can create logographic and alphabetic reading using the novel orthography paradigm. Under the assumption that logographic reading entails no or limited understanding of an underlying sublexical structure leading to poor transfer of knowledge to novel and pseudoword items, we argue that using a holistic training paradigm with Korean Hangul orthography that we can create such readers. We look to compare the effects of this type of training compared to explicit alphabetic training to determine the differences in behavioral and cortical outcomes.

Participants

Thirty right-handed, native English speaking, participants (18 female and 12 male) recruited from the University of Pittsburgh campus and surrounding region volunteered to participate in this experiment. The mean age of the participants was 26.4 (ranging from 19-48).

These participants were naïve to the project hypotheses but were given brief details that they would be learning to read words in a different language during recruitment. Participants gave informed written consent and were rewarded monetarily for their cooperation. All subjects reported normal hearing, no history of learning or reading disability, and normal, or corrected-to-normal, vision.

Design

The primary variable in the experiment, Holistic versus Component training, was manipulated between-subjects. A third "Control" group was also provided an abridged version of the training paradigm to serve as a training baseline group for the fMRI portion of the experiment. Ten subjects were randomly assigned to each of the three groups; however, two subjects from the component condition did not complete the scanning session due to technical difficulties. Frequency of trained word items was manipulated as a within-subject factor. Participants in the Holistic and Component conditions were trained in 4 separate Sessions and assessed at three intervals within each session. A fifth session assessed performance on a range of tasks occurring on the day of the MR portion of the experiment. Participants in the Control group received one brief training session on the day of the MR experiment. Learning was assessed across sessions in two separate procedures: a Word Identification and a Forced-Choice Recognition. At the fifth session, the generalizability of knowledge was tested in a Novel Word and Pseudoword Identification task.

Materials & Procedure

In this novel orthography training paradigm, we utilized the **Korean Hangul** writing system, which is alphabetic but visually distinct from Roman-based linear alphabetic writing systems. We adapted the Hangul alphabet to further reduce the similarity from native to novel writing systems in the learning paradigm. Subjects were trained to read words written in Korean Hangul containing graphs that correspond to phonemes of the native spoken language (English). We attempted to preserve the grapheme-phoneme relationship of the Korean graphs used in the study since it has been suggested that the graphemes reflect the articulatory aspects of labial and velar positions of the phonemes themselves. The composition of Hangul letters follows a square structure, or Kulja, in which the letters are arranged both left-to-right and/or top-to-bottom, as illustrated in Figure 2. This Kulja package corresponds to a single, typically C-V-C syllable.

We took advantage of this varied stacking to encourage treating this as a novel encoding task and thus reducing interference from mapping the linear form of the Roman alphabet to this novel orthography. In contrast to other writing systems, Hangul was more invented than developed, and its letter-phoneme correspondences are completely transparent. Thus, we used this characteristic to create a perfect orthography (a single letter maps to a single phoneme) with a subset of letter-sound units consisting of 8 consonants and 4 vowels. Certain phonemes such as /k/ and /i/ (long E sound) were selected to make the mapping to the native English orthography difficult, for example, the letter corresponding to /k/ is presented in the words "cat" and "kit" making a strict mapping difficult.

We created 80 word stimuli with simple consonant-vowel-consonant (CVC) structures for the set of training items. Of the 80 word stimuli, each of the four vowel units were represented equally such that there were twenty words containing each vowel in the middle position. Initial consonant units were also equated with 10 words created for each of the eight consonant unit in the word onset position. Final consonants were roughly equated in that each consonant was represented between 8-12 times in the final position. To reduce the likelihood that participants would implicitly derive the alphabetic code, words with repeating consonants (e.g. bib) were disallowed in the training portion of the experiment. These words do appear in the novel word assessments in Session 5 and the fMRI scanning stimuli. The resulting words were assigned to four sets (A, B, C, and D) pertaining to the 4 training sessions, 1 per day, in which a new set is introduced each session. Each set contained equal number of word items for each vowel unit and were roughly equivalent for consonant onset units. We manipulated the frequency of exposure to word items by exposing a subset of words learned in previous session in all future session, such that half of the Set A words (n=10) encountered in Session 1 also appeared in training Sessions 2-4 and half of the words in Set B were presented in Sessions 3-4 and so on (see Table 5 for details).

Pre-Training

Prior to training, we assessed word decoding ability by administering the Woodcock-Johnson (Woodcock & Johnson, 1989) Word Attack—pseudoword battery to all participants. The battery consists of 45 pronounceable non-words in order from simple two-phoneme sequences to four syllable complex stimuli. Items are to be pronounced based on common rules or consistencies of the English language. Pronunciation errors in any portion of the items were scored as incorrect responses. Individual accuracy scores were compiled for each subject out of a possible total score of 45.

Training

All subsequent training and assessment measures were administered using E-Prime experimental software (Psychology Software Tools, Inc.) on 800+ GHz PC computers. Participants were pseudorandomly assigned to the two conditions, holistic and component (phonics-based) training, based on an A-B-B-A permutation. Participants were trained in four separate **Sessions** across four days (1 per day). Each session lasted approximately one-hour.

Participants were instructed that they were to learn spoken English word forms (e.g. cat, bit, etc.) printed in a novel orthography, namely Korean Hangul. In each session, participants were trained on a unique set of words and presented with a subset of words learned from previous sessions that made up the high frequency (**HF**) set of items. Training took place in 2 **Learning Blocks** per session; each training block was followed by a testing block. In sessions 2-4, participants were tested at the start of the session prior to the learning trial to measure retention of previous items and transfer of knowledge to novel items (i.e. items to be learned in the current session). At the final session, participants were given several dependent measures to assess level of retention and overall skill. The diagram in Figure 1 illustrates the general procedure within and across sessions for participants in both training conditions.

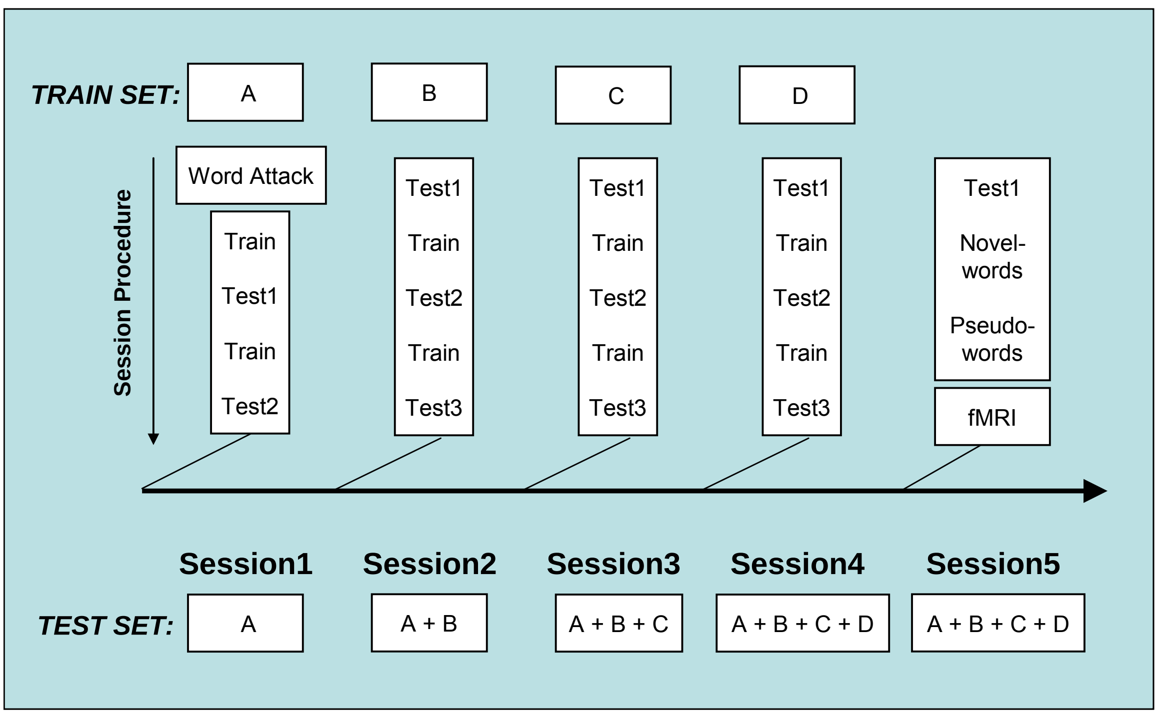

Figure 1. Diagram of Session Procedure for Experimental Training Groups. A new set of training words (TRAIN SET) are introduced at each session; however, participants are tested (TEST SET) on previous and current trained items. Training occurs over two blocks for each session and testing occurs at intervals before and after the training blocks

In each session, participants were to learn 20 new word items repeatedly presented in the 2 Learning Blocks mixed in with trials for the HF items from previous sessions. In each Learning Block, new and HF items were each randomly presented 8 times, such that each word was presented a minimum of 16 exposures (See Table 1 for frequency of word items). Each training trial lasted for a duration of 4 seconds. In the **holistic** training condition, a whole word stimulus appeared in red followed 500ms later by its pronunciation ("cat"). The visual word stimuli remained on the screen for at least 4 seconds (see Figure 2 Bottom). When the trial expired, the next item appeared. In the **component** training situation, the entire word symbol was presented with the first component highlighted in red for 1000 msec with the other letters in light blue, followed by the second then third components, after which the entire stimulus was highlighted in red for the remainder of the trial (see Figure 2 Top) total time 4 seconds. As each individual grapheme was presented, the corresponding phonemes (/k/+/a/+/t/) were heard through headphones simultaneously with the onset of the visual stimuli. Then, the phonological word ("cat") was presented simultaneously with the onset of the whole visual word, which remained on screen for the remaining (1) second or until the participant pressed the spacebar. Again, after the trial was terminated, the screen advanced immediately to the next word trial.

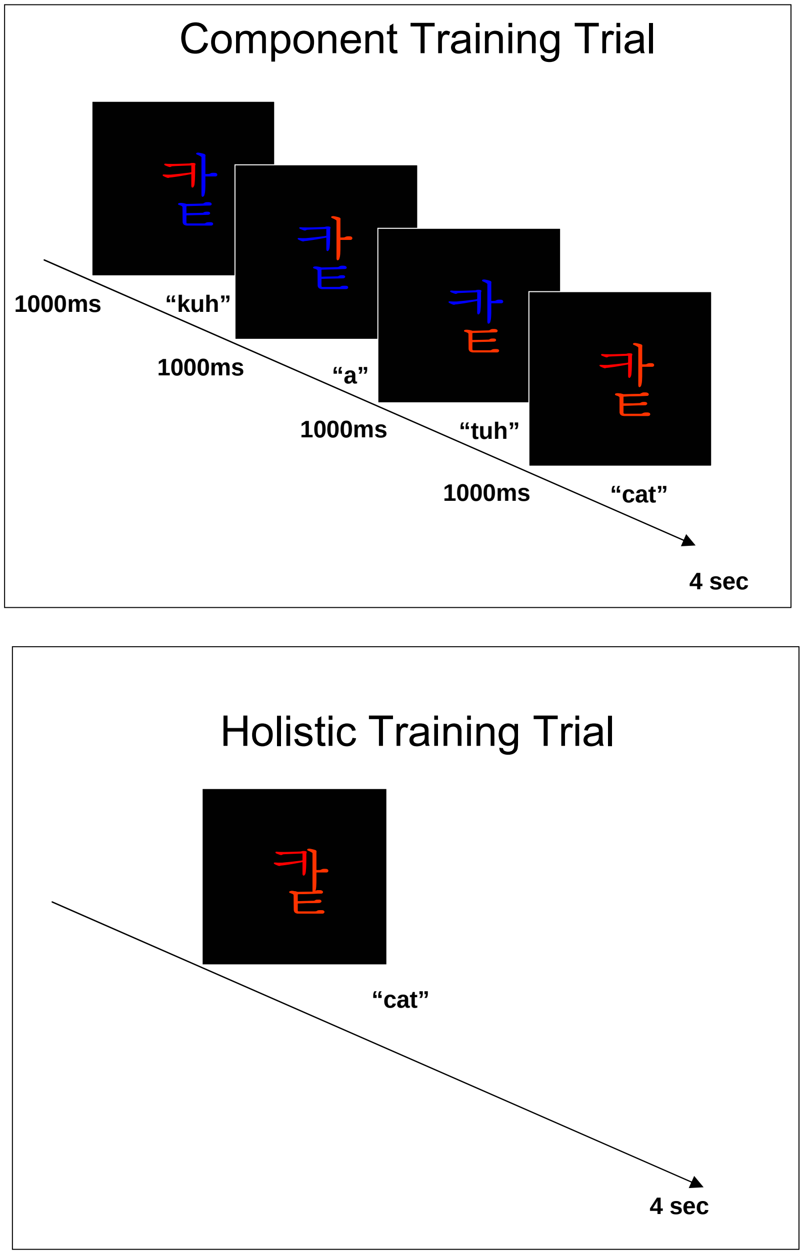

Figure 2. Diagram of Training Trial Procedures for the Component Group (Top) and the Holistic Group (Bottom).

Training conditions were matched for exposure duration to each word stimulus (4sec).For the purposes of investigating the overall impact of training on the plasticity of cortical regions, a third training condition was developed to serve as a low-trained group. Ten participants were randomly assigned to this **Control** group. These participants were also administered the

WordAttack pseudoword battery prior to training. They were trained in a single Training Block on all 80 word items presented 8 times each via the ***holistic*** (whole word) training method. The effects of training for these participants were assessed at a single Testing Period following the training block. These participants were assessed via the Recognition task only (described below) and not on the Identification task due to the difficulty of the latter task. The training session was conducted on the same day of the fMRI scan. Control group participants were also required to fill out the Exit Interview as described below.

Testing

Two dependent measures were collected throughout the training sessions to assess word learning at regular intervals. The first test, the word identification task, required the participant to read aloud a word (printed in Korean orthography) from the training materials that was visually presented in isolation for a maximum of 8 seconds or until the participant made a response. Verbal responses made by participants were recorded via audiotape and by the experimenter, who also coded the accuracy of the utterance on a scoring sheet for analyses. Following the verbal response, the participant hit the spacebar to advance to the next trial. Words were each presented one time in pseudorandomized order using 4 randomized lists which were randomly assigned to participants by subject number prior to the study. For each session, words that were presented on the current training set and all prior training sets were assessed as shown in Figure 1 and Table 1. Thus, at Session 1, only words from Word Set A were administered in the task, at Session 2, words from Set A and B were administered, and so on (see Figure 2 for details). Participants were tested in each training session at 3 separate intervals: 1) before training, 2) after the first training block, and 3) after the second training block—at Session 1, participants were not assessed before training and thus only received 2 testing periods. At each testing period, each trained item was presented once in this task resulting in an increasing test duration from 20 trials at each period in Session 1 to 40 trials in Session 2, 60 trials, in Session 3, and 80 trials in Session 4.

Table 1. Number of Training Trials for High Frequency words in each WordSet by Session

	Training Session				Total Occurrences	
Training Set	**Session 1**	**Session 2**	**Session 3**	**Session 4**	**Hi Freq**	**Low Freq**
Set A	**16**	**8**	**8**	**8**	**40**	**16**
Set B		**16**	**8**	**8**	**32**	**16**
Set C			**16**	**8**	**24**	**16**
Set D				**16**	**16**	**16**
Test Set	*A*	*A+B*	*A+B+C*	*A+B+C+D*		

Following the Identification task, a second assessment measure, a forced-choice (match-to-sample) recognition task, was collected. This task required participants to select the appropriate matching visual stimulus to an auditory cue. Participants were presented with an auditory word stimulus followed by four visual word stimuli (a trained word and three foils) and asked to identify the matching word stimulus. Three conditions of visual word foils were created for each trained word, each sharing two of the following grapheme-phoneme units: first consonant, middle vowel, or final consonant with the target word. In this task, the auditory stimulus was presented for a maximum duration of 35-50ms. After 500ms, the four visual word choices were then presented horizontally across the screen (each item presented with the response number 1-4 immediately to the left) for a maximum duration of 8 seconds or until the participant responded by making a keyboard response of 1 through 4. The target words, presented auditorally, were drawn from the identical list of items as in the Identification task (i.e. all current and prior trained items).

Assessment measures were collected at three separate intervals during each session. The first testing interval occurred prior to the training blocks in each session. These tests consisted of words that were to be trained in that session enabling us to acquire a measure of transfer from the previous set(s) of words to the untrained words. These tests also consisted of words trained in the prior sessions which allowed us to measure the retention of knowledge between sessions for the previous set of words without the confounding influence of practice effects and interference effects from the new training set.

A fifth "Session" was conducted prior to the imaging portion of the study. In this session, participants were administered the Word Identification and Forced-Choice Recognition tasks for all trained words. These tasks were followed with a Novel Word Identification task and a Pseudoword Identification task under the identical procedure for the Word Identification task. For the Novel Word task, participants were presented with 40 legal English CVC words using the same set of twelve Hangul graphemes (and corresponding phonology) as in the training set. Items were matched for initial consonant (5 items per consonant) and middle vowel (10 items per). The participants were asked to read the set of novel word items aloud as in the Word ID tasks. Presentation of the stimuli followed the same parameters as the Word ID task as well. In the Pseudoword ID task, 40 non-lexical (for English) CVC items were created using the same procedure as the novel words. Stimulus presentation was also the same as in the previous task.

The fMRI portion of the experiment occurred after the completion of Session 5. The detailed methodology is described in the next chapter.

Exit Interviews

Following the fMRI scanning portion of the experiment, the participants were administered an Exit Interview which consisted of two components. The first task required the subject to a) produce the 12 visual symbols or graphemes of which the words were composed and then b) produce the appropriate sound or phoneme for that symbol. The second question prompted the participants to subjectively describe the strategy(ies) they employed in the training component of the study. They were prompted by the experimenter to be as descriptive as possible detailing any changes in strategy and when they occurred during training.

Analyses

The dependent measures of interest are transfer to new words and retention of knowledge across session, and generalizability to novel and pseudoword reading. We measured transfer by looking at performance on novel word and pseudowords created using the learned units. Retention was measured word recognition performance at +1, +2, +3, +4 sessions. Transfer was assessed by examining performance on novel words not previously encountered on the Identification and Recognition task. We examined both reaction time and accuracy data to assess the amount of word learning achieved from training conditions.

Results

Behavioral Task Analysis

Analyses of the two behavioral tasks, Word Identification and Forced-Choice Recognition task, were conducted to test training-related differences in a) transfer of knowledge, b) retention of knowledge, and c) the interaction of training with frequency of exposure comparing high (HF) and low (LF) frequency words. The data reported for these tasks are based on the participants who participated in the entire experiment including the scanning portion. Thus, a series of Mixed model repeated-measures ANOVAs were conducted on the dependent measures comparing the component-based (n=8) and holistic (n=10) training groups. The Control group is not included in these analyses because the nature of this group's experience is so distinct from the other training conditions. Because a voice-key was not used to provide appropriate latency data, accuracy is the sole dependent variable in the Word ID task. In the Recognition task, both accuracy and response time were used as dependent measures. After the first set of analyses were conducted, variance observed in the Holistic training group revealed a non-homogeneous set of subjects, rather evidence of a bimodal distribution in participant performance emerged (see Figure 3B). Accuracy for a subset of the holistic training group (n=5) performed at ceiling on the WordID and Recognition tasks, whereas the second set (n=5) performed far less accurately on these tasks. In a separate set of analyses, we subdivided the holistic group according to this bimodal distribution, a high skill group (HS) and a low skill group (LS), and compared the performance of these subsets.

Word Identification

Accuracy, in terms of proportion correct, was compiled for individual Word Sets according to the Test Periods of each Session. The data displayed in Figure 3A show the means for each Training Method according to Word Set at each Test Period (by Session). The data displayed in Figure 3B exhibits the mean accuracy for high and low performing participants within the holistic training condition.

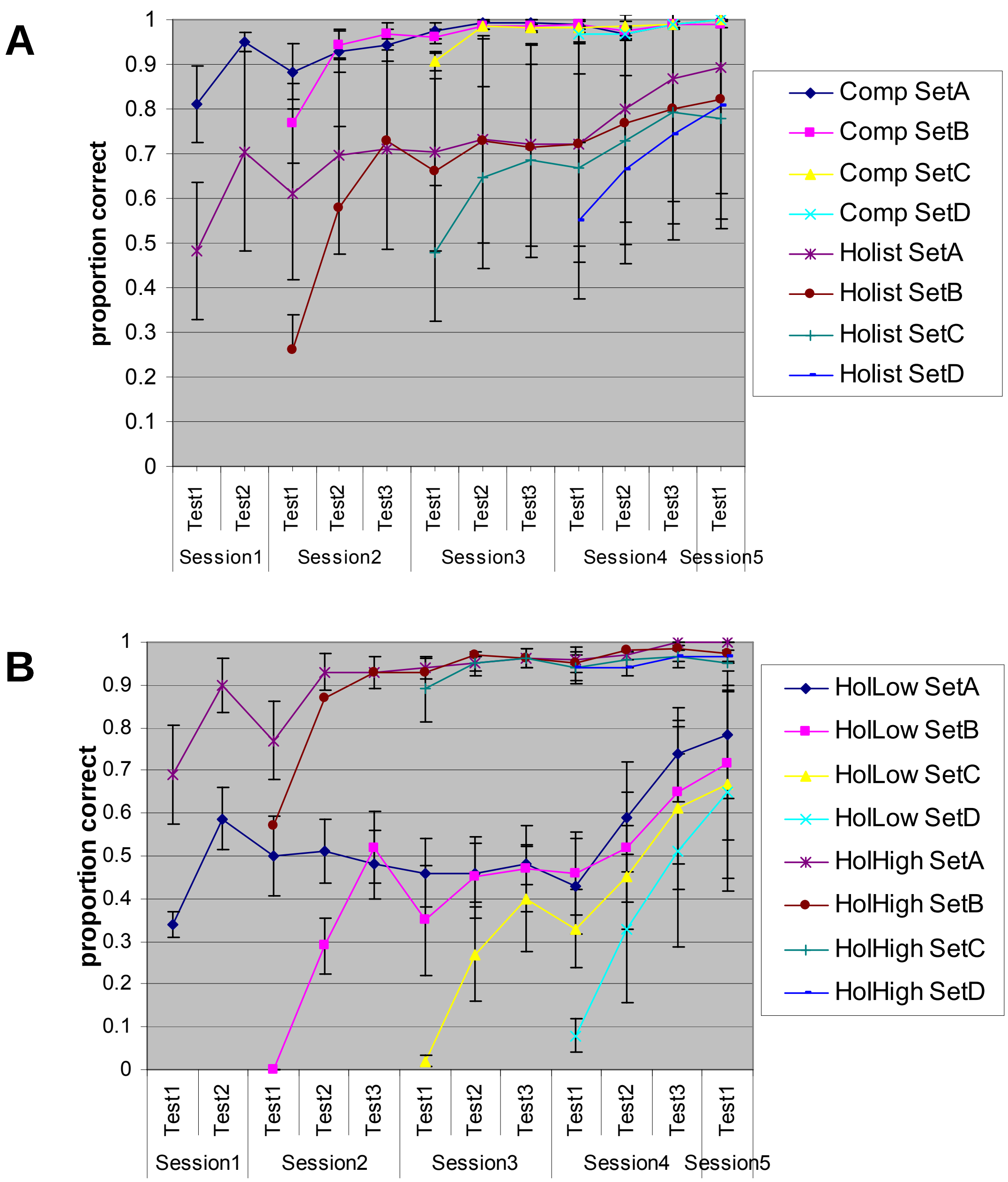

Figure 3. Word Identification accuracy comparing groups for each Word Set by Test Period. The top graph compares means for the Holistic compared to Component training conditions. The bottom graph compares the high performing with the low performing participants in the Holistic Training condition. Each series (line) represents performance for a single Set of words.

Effects of Training on Transfer

We hypothesized that the component group would internalize the letter-sound code sufficiently to enable transfer in terms of accurate decoding of novel words. In order to test the effects of transfer, subject means were analyzed from the initial Testing Period for each Word Set (Session 2 Set B, Session 3 Set C, and Session 4 Set D) prior to actual training on those items. A mixed model repeated-measures ANOVA was conducted with training condition as a between subjects factor and WordSet (at Test1 in respective sessions) as the within-subject variable. The results of this test revealed a main effect of Training Method in which the Component group was far more accurate (mean=0.88) than the Holistic Group (mean=0.43) on these unknown items, $F(1,17)=10.80$, $p<0.005$. This test also revealed a significant effect for WordSet $F(2,16)=7.893$, $p<0.005$, such that overall subjects were more accurate on Set 4 (mean proportion correct = 0.76) than Set 3 (mean=0.70) which was more accurate than Set 2 (mean=0.51). Post-hoc comparisons confirm this result: Set 4 > Set 3 ($p<0.01$) and Set 3 > Set 2 ($p<0.01$). There was no interaction between Training Method and WordSet, suggesting that, despite the gap in overall accuracy, groups made relatively equal gains from session to session.

Effects of Training on Retention

We also hypothesized that learning the sublexical components explicitly would enable more efficient acquisition of word forms because of the redundant mechanism of decoding knowledge would enable the 'bootstrapping' of lexical forms. We predicted that the component group would better retain word form knowledge over time than the holistic group. In order to test the *rate of retention*, the subject-wise accuracy values were calculated for Word Sets A-C in the following Session (all 3 Testing Periods per Session). A mixed model repeated measures ANOVA was conducted with Training Method as the between-subjects variable and WordSet and Test Period (1, 2, and 3) as within-subject factors. Results of this test revealed a main effect of Test Period, $F(2,54)=11.36$, $p<0.001$, with participants performing more accurately at Test3 (mean=0.85) and Test2 (mean=0.83) compared to Test 1 (mean=0.78). Planned comparisons reveal significant finding between Test 3 and Test1 ($p<0.001$) and between Test2 and Test1 ($p<0.001$) suggesting that the latter testing periods are likely confounded by subsequent training on Set items in the HF condition as well as from novel Set items. Thus, all future tests of Retention consisted of means at Test Period 1 of the following Session after initial training on those words (i.e. Set A at Session 2, Set B at Session 3, etc.). The ANOVA model was re-run with Test Periods 2 and 3 removed from the analyses. The results of this model found no effect of WordSet and no interaction between WordSet and Training Method. However, a main effect of Training Method was found, $F(1,17)=9.43$, $p<0.01$, with Component trained subjects performing more accurately (mean=0.94) than Holistic group subjects (mean=0.65). Thus, our predictions regarding retention were confirmed. This effect supports our prediction that component training results in more reliable acquisition of word form knowledge and thus better retention performance than holistic training.

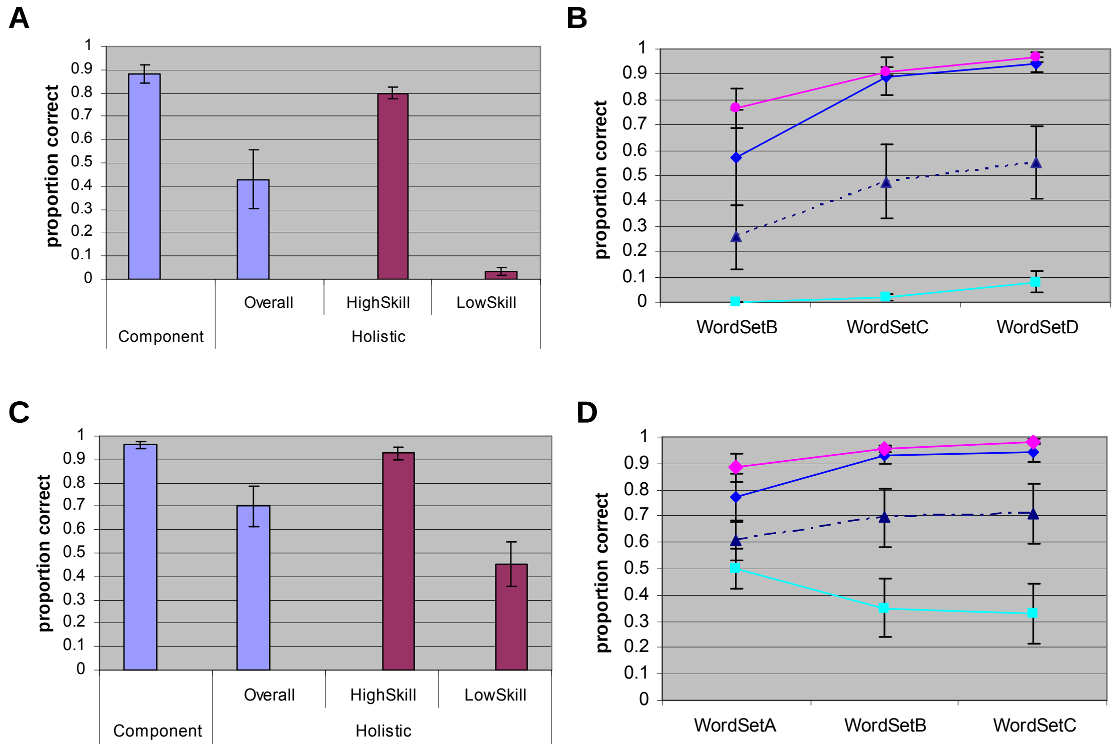

Figure 4. Effect of Transfer (Top) and Retention (Bottom) for Word Identification Accuracy by Group. The graphs on the left (A & C) display the main effects by group. Statistical comparisons were done contrasting Component and Holistic training groups (blue bars) and contrasting High and Low performing subsets of the Holistic training condition (red bars) for Transfer (Top) and Retention (Bottom). The graphs on the right (B & D) depict the effects of transfer and retention as a function of time via Word Set performance. Mean accuracies are displayed for the component group (pink), the holistic group overall (blue dotted), the high performing holistic subset (solid royal blue) and low performing holistic subset (solid light blue).

Frequency Effects by Training Condition

Based on previous findings in the literature, we argued that explicitly trained participants internalize the letter-sound components of the system providing them with redundant systems of phonological decoding knowledge and specified word form knowledge to identify words (Perfetti, 1992). In English, frequency effects are not observed for words with highly consistent spellings (McClelland & Seidenberg, 1989; Jared, McRae, & Seidenberg, 1990). Thus, we predicted that explicitly training on components would result in no effects of frequency compared with holistic word training which would be more susceptible to these effects. To test the overall effect of frequency of exposures to word items and the interaction with Training Method, we combined the mean accuracy for each subject at the final two Test Periods (Session 4 Test3 and Session 5) for individual Word Sets. In these analyses, it is important to note that the effect of WordSet is critical since HF words in Sets A, B, and C are exposed in training trials across all session 64, 48, and 32 times respectively. We conducted a repeated measures ANOVA to compare performance on HF and LF word for WordSets A, B, and C between Training Methods. There was also a main effect of frequency, $F(1,34)=6.99$ $p<0.05$, with subjects performing more accurately on HF (mean=0.89) compared to LF (mean=0.87) items. The effect of frequency significantly interacted with Training Method, $F(2,34)=7.17$ $p<0.05$, in such a way that the Component group elicited no change in performance from HF to LF words (mean=0.98 for both conditions) whereas the Holistic group was affected by frequency (means=0.80 for HF and 0.75 for LF). A significant main effect between Component and Holistic training groups was also found, $F(1,17)=4.32$ $p<0.05$, with the former group (mean=0.98) outperforming the latter group (mean=0.77). The results of this tests revealed a trend of WordSet ($p=0.06$) with subjects performing better on Set A (mean=0.90) compared to Set B (mean=0.88), $p<0.05$, and generally better than Set C (mean=0.86)—however, no statistical significance shown. The means for this comparison are displayed in Figure 5.

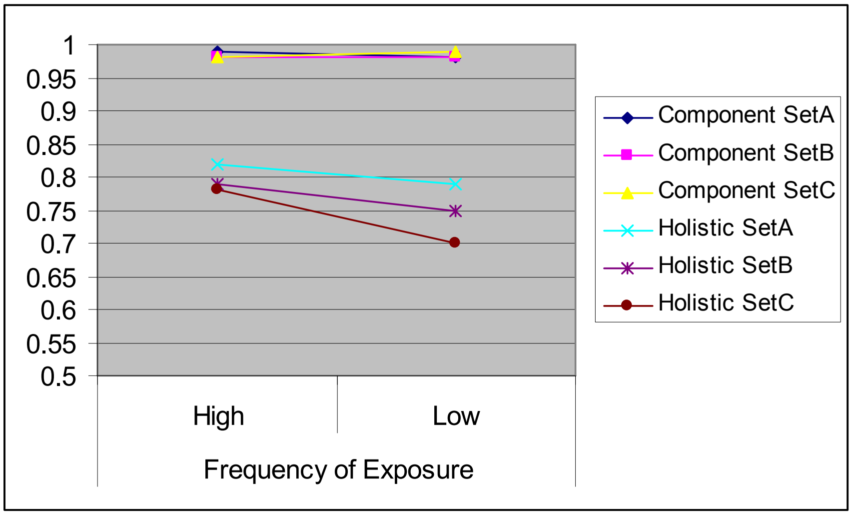

Figure 5. Effect of Frequency on Word Identification Accuracy by Training Group for WordSets A,B,C

Effects of Transfer from Holistic Training

We asked whether holistic training would result in implicit derivation of the letter-sound code or if it would lead to logographic reading. Based on the data when can strongly argue in favor of both outcomes, that is, holistic training revealed both implicit learning of components and more logographic outcome in different participants. A primary mode of distinguishing whether these performance differences reflect underlying knowledge of the sublexical components is to test the transfer of knowledge to new items. When the holistic group was divided into two skill groups HS and LS, the analyses revealed unique patterns in transfer performance. We conducted a repeated-measures ANOVA on the ten participants in the holistic group with Skill as a between-subjects factor. The difference between Skill levels was substantial, $F(1,8)=94.04$, $p<0.001$. The mean proportion correct for the HS group moved quickly to ceiling (0.80) whereas the LS group performed poorly (mean=0.03). The resulting means of these groups are displayed in Figure 4(A-B), which shows the clear differences between these groups as well as the positive gains across sessions. The statistical tests revealed a marginal effect for word set, $F=4.47$ ($p=0.059$), which showed a positive linear trend from Set 2-4, $F(1,8)=6.47$, $p<0.05$. There was no interaction between Skill Level and WordSet.

Holistic Training Differences on Retention

If the participants in the holistic condition were able to acquire the letter sound code, we argued that it is the internalization of the letter-sound code that enables more accurate formation of word form representations. Thus, we predict that those that acquire the code will perform better on tasks of retention than those holistically trained participants that do not. We again the differences in retention between Skill levels within the Holistic Group in a repeated measures ANOVA with Skill as a between-subjects factor that revealed that the high skill group (mean=0.88) outperformed the low skill group (mean=0.39) [$F(1,9)=22.15$, $p<0.005$]. We also found a significant interaction between WordSet and Skill Level $F(1,9)=5.57$, $p<0.05$. This interaction, displayed in Figure 4 (D) by the solid blue lines, is reflected by gains made from WordSet A to B to C for the high skill group (means=0.77, 0.93, and 0.94 respectively) whereas the low-skill group show losses in subsequent WordSets (means=0.50, 0.35, and 0.33 respectively). Thus, not only do the high performing participants outperform the low performance group on the retention task as predicted, but the retention of word knowledge increases for those that implicitly derive letter-sound knowledge, and decreases over time for those who do not derive the code.

Frequency Effects on Holistic Training Group

If the letter-sound code is implicitly derived in holistic training the internalization of the letter-sound code would result in minimal impact of frequency. On the other hand, we argued that the logographic reading in which sublexical components are not acquired is heavily dependent on paired-associate learning mechanisms and thus highly susceptible to effects of frequency. We compared the effect of Frequency across Skill level within the Holistic group in a repeated-measures ANOVA. These analyses revealed a marginal interaction between frequency and skill level, $F=4.52$ $p=0.07$ in which participants in the Low skill group were more affected by frequency (mean=0.57 for HF compared to 0.49 for LF items) than the high-skill group (mean=0.98 compared to 0.97 respectively). An overall effect of skill level was observed, $F(1,8)=9.41$ $p<0.01$, where high skill participants (mean=0.97) outperformed low skill participants (mean=0.53) across items. These results also revealed a main effect of WordSet as seen in the previous test, $F(2,16)=4.91$ $p<0.05$, with performance on Set A (mean=0.79) marginally better than performance on Set B (mean=0.75), $p=0.06$, and better than Set C (mean=0.72), $p<0.05$. Therefore items which were seen more often were more likely to be identified correctly. An overall main effect of frequency was also present, $F(1,8)=11.31$ $p<0.01$, as participants in this analysis performed better on HF (mean=0.78) compared to LF (mean=0.73) items. These analyses confirmed the notion that internalizing the letter-sound code reduces the effects of frequency.

Forced-Choice Recognition Task

For the Recognition Task, the dependent measures of proportion correct and mean decision times were tested separately. Each of these dependent variables were analyzed using repeated-measures ANOVA models for between and within-subject effects as conducted in the Identification task. As for response time, the reported results reflect performance on all responses due to the limited set of data by condition. The data displayed in Figure 5 show the mean accuracy for each Training Method according to Word Set at each Test Period (by Session) and Figure 6 displays the response time data for these same conditions. The data for the Holistic group reflected the bimodal distribution seen in the Word Identification task. A separate set of tests were run for the dependent measures of this task as well to test for transfer, retention, and frequency effects as a function of skill.

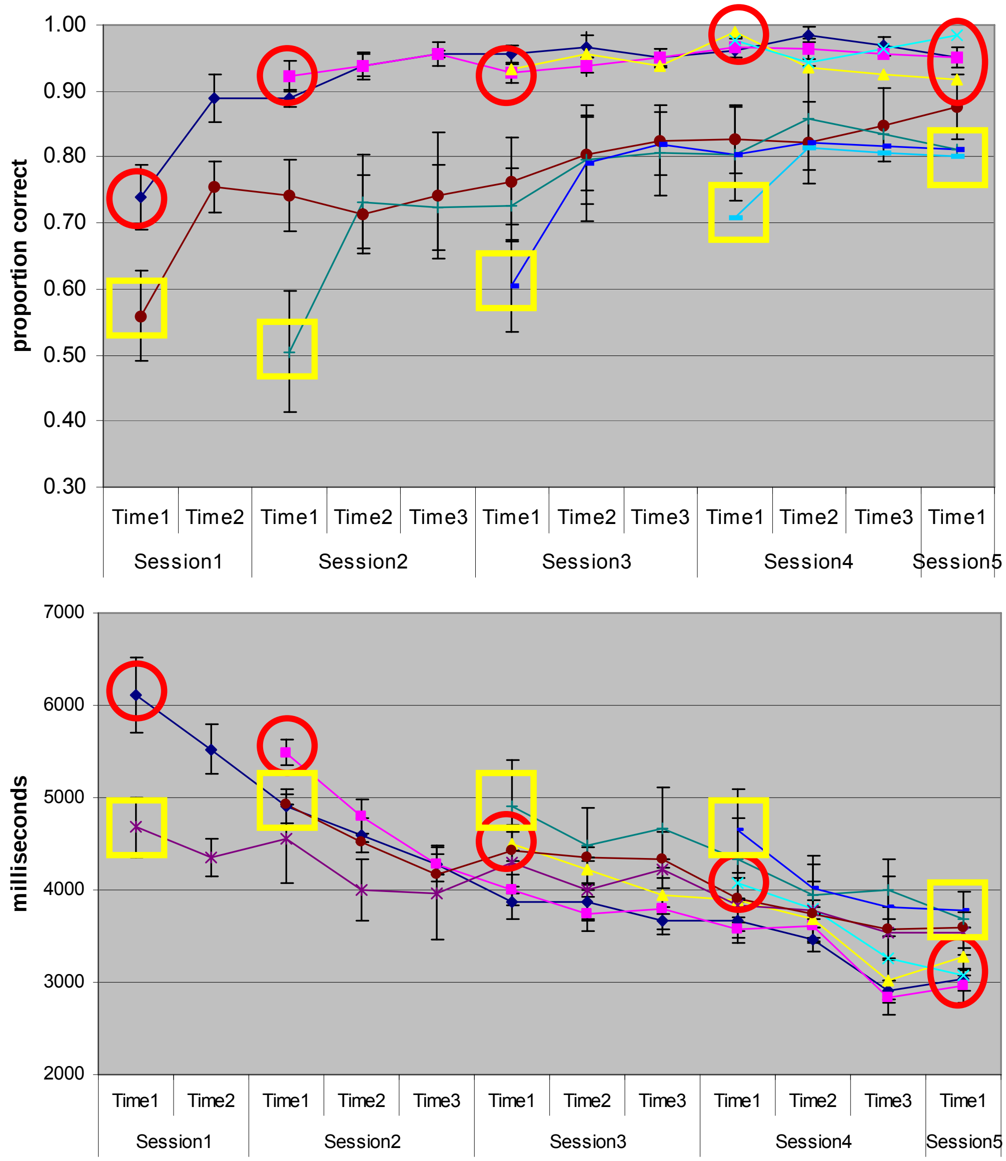

Figure 6. Recognition Task accuracy comparing Component and Holistic groups by Test Period The top graph compares mean accuracy for the Holistic compared to Component training conditions. The bottom graph compares mean response time for the Holistic compared to Component training conditions. Each series (line) represents performance for a single Set of words. Initial performance for each set are marked by red circles for the Component group and by yellow squares for the Holistic group. These points represent the effect of transfer from session to session.

Effects of Training on Transfer

We tested the prediction that component training leads to better transfer than holistic training for recognition accuracy. In order to test the effects of transfer, subject means were analyzed from the initial Testing Period for each Word Set (Session 2 Set B, Session 3 Set C, and Session 4 Set D) prior to actual training on those items. A mixed model repeated-measures ANOVA was conducted for mean accuracy with training condition as a between subjects factor and WordSet (at Test1 in respective sessions) as the within-subject variable. The results of this test revealed a main effect of Training Method, such that the Component group was far more accurate (0.90) than the Holistic Group (0.61) on these unknown items, $F(1,17)=9.65$, $p<0.01$. This test also revealed a significant effect for WordSet $F(2,32)=4.62$, $p<0.05$, such that overall subjects were more accurate on Set D (proportion correct = 0. 84) and Set C (0.77) than Set B (0.71). Planned comparisons of the three sets confirms this trend, Set D > Set B ($p<0.05$) and Set C > Set B ($p=0.06$). There was no interaction between Training Method and WordSet.

We tested the prediction for differential training effect on transfer performance for recognition decision times. The repeated-measure ANOVA test was employed for the response time data. The interaction between WordSet and Training Method was marginally significant, $F=3.13$ $p=0.06$. As shown in Figure 7(D), Component group response times drop considerably from SetB to SetC to SetD (5458, 4429, and 3987ms) whereas the overall performance of the Holistic group remains relatively unchanged (4923, 4913, and 4639ms respectively). Because the Component group is comparatively slower at SetB but faster at SetD than the Holistic group, no main effect of skill is seen. This effect is entirely consistent with our stated hypotheses regarding these training differences. The tests also revealed an overall effect of WordSet, F(1,16)=5.91, p<0.01, with longer latencies for SetB (5191ms) compared to SetC (4671ms), p=0.08, which were longer than SetD (4313ms), p<0.05.

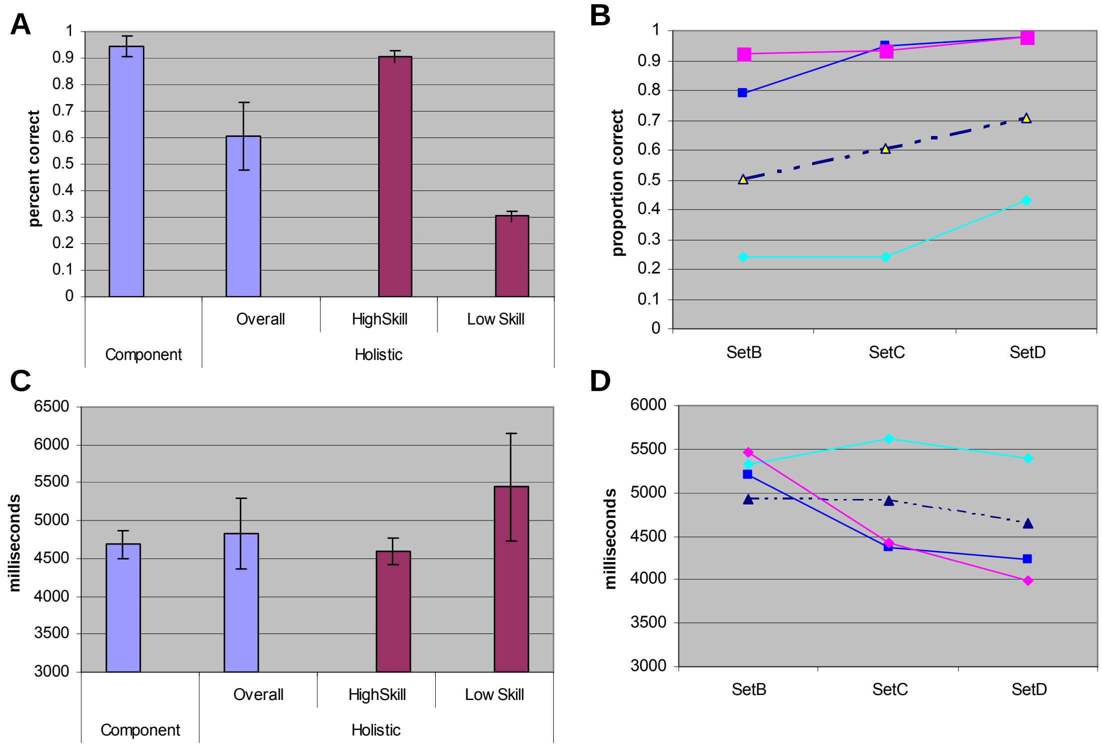

Figure 7. Effect of Transfer for Recognition Task Accuracy (top) and Response Time (bottom) by Training Group. The graphs on the left (A & C) display the main effects by group. Statistical comparisons were done contrasting Component and Holistic training groups (blue bars) and contrasting High and Low performing subsets of the Holistic training condition (red bars) on mean Accuracy (Top) and Response Time (Bottom). The graphs on the right (B & D) depict the dependent measures as a function of time via Word Set performance. Mean accuracies and response times are displayed for the component group (pink), the holistic group overall (blue dotted), the high performing holistic subset (solid royal blue) and low performing holistic subset (solid light blue).

Training-related effects on Retention

We predicted that component training, compared to holistic training, will result in greater retention in terms of more accurate performance on trained items. Retention was analyzed by comparing mean accuracy for Word Sets A-D at Test Period 1 of the Session occurring 24 hours after initial training on those words (i.e. Set A at Session 2, Set B at Session 3, etc.). A mixed model repeated measures ANOVA was conducted for WordSets A, B, and C with Training

Method as the between-subjects variable. Results of this test revealed a main effect of Training Method, $F(1,16)=7.76$ $p<0.05$, with the Component group performing more accurately (mean =0.94) than their Holistic group counterparts (mean=0.76; see Figure 8A). This test also revealed a main effect of WordSet, $F(2,32)=5.76$ $p<0.01$, as participants were more accurate on Set C words (0.90) compared to Set B (mean=0.83) words, $p<0.01$, or Set A words (mean=0.82), $p<0.01$ (see Figure 8B). There was no interaction between WordSet and Training Method. These results confirmed our overall hypothesis that the component training yields better performance than holistic training on trained items.

We tested the predictions regarding training-related differences in recognition decision times for recently learned words. Statistical tests were conducted to determine differential effects of Training Method on the retention of knowledge based on the RT data. As shown in Figure 8D, the data reveal that the component group is initially slower than the holistic group on Word Set A (mean=4926ms compared to 4550ms), becoming faster on Sets B and C for the component group (means=3966ms and 3829ms) while remaining stable for the holistic group (means=4422ms and 4330ms). However, no main effect of training method or interactions are found. This is likely due to the variability in the Holistic group (SE=373ms) compared to the Component group (SE=141ms). These analyses revealed only main effects of WordSet, $F(2,32)=4.21$ $p<0.05$. Participants were slower to respond to Set A words (4738ms) than they were to either Set B (4194ms), $p<0.05$, or Set C (4080ms) items, $p<0.05$. Thus, decreases in responses times are observed for the component group but not the holistic group; however, due to the variability this interaction was not significant. However, as we will see below, when the holistically trained group are divided by skill our predictions are supported.

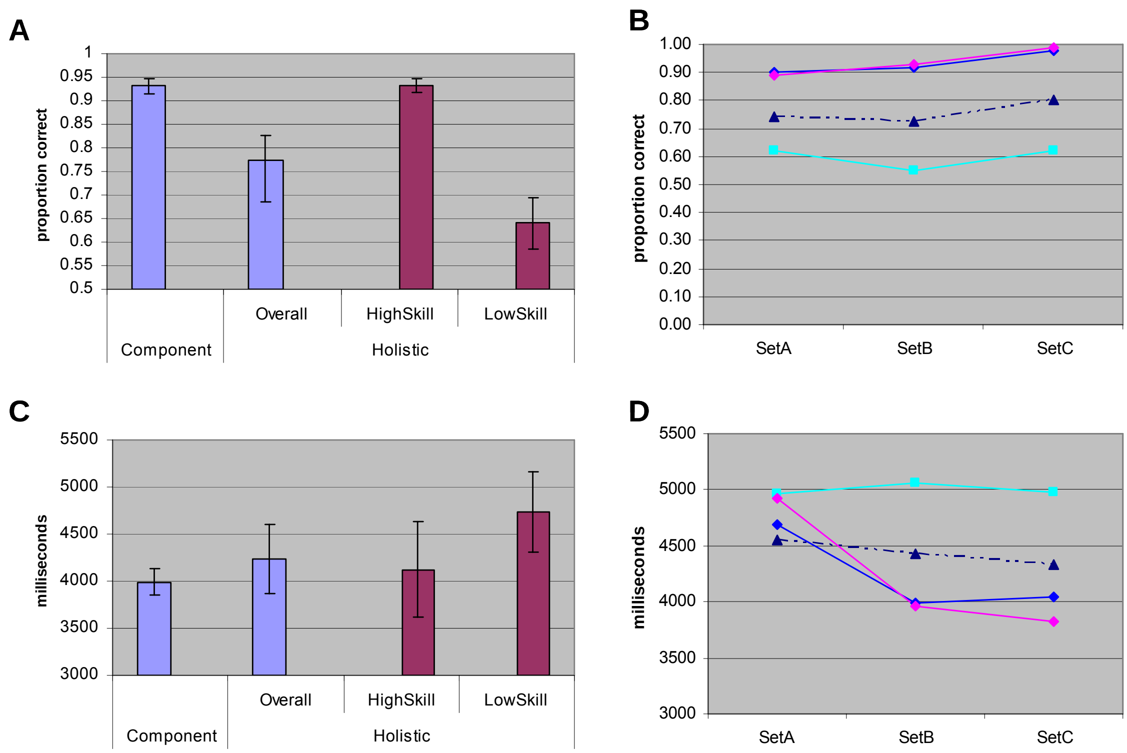

Figure 8. The Effect of Retention for Recognition Task Accuracy (top) and Response Time (bottom) by Training Group. The graphs on the left (A & C) display the main effects by group. Statistical comparisons were done contrasting Component and Holistic training groups (blue bars) and contrasting High and Low performing subsets of the Holistic training condition (red bars) on mean Accuracy (Top) and Response Time (Bottom). The graphs on the right (B & D) depict the dependent measures as a function of time via Word Set performance. Mean accuracies and response times are displayed for the component group (pink), the holistic group overall (blue dotted), the high performing holistic subset (solid royal blue) and low performing holistic subset (solid light blue).

Effects of Frequency for Training

We tested the prediction that training conditions would differ with respect to the effect of training frequency on word items for recognition accuracy. We conducted separate tests with Training Method and Skill level within the Holistic Group as between-subject factors. These tests reveal no significant effects for frequency suggesting that, unlike the Word Identification task, accuracy on the Recognition task is relatively insensitive to this factor.

We tested the same prediction that, compared to component training, holistic training would result in better performance for high versus low frequency words in terms of faster recognition response times. Thus, we predicted an interaction between training method and item frequency such that the holistic group would show sensitivity to frequency whereas the component group will not. The statistical tests frequency effects on response time did produce a number of significant findings. A repeated-measures ANOVA testing the effect of frequency between Testing Methods revealed an overall effect of frequency [$F(1,16)=4.69$, $p<0.05$] for HF items (mean=3441, SE=168) compared to LF items (mean=3578, SE=197). The predicted interaction was supported by the trends in the means such that the component group was equally fast at HF (mean=3312ms) and LF words (mean=3386ms) whereas the holistic group performed more slowly for LF (mean=3770ms) compared to HF (mean=3571ms). However, this interaction was not statistically significant. Other results revealed a main effect of WordSet [$F(2,32)=7.80$, $p<0.005$] with participants performing more slowly on Set C items (mean=3698ms, SE=217) compared to SetB (mean=3414ms, SE=181, $p<0.005$) and SetA (mean=3418ms, SE=154, $p<0.05$) in pairwise comparisons. A significant interaction was found between frequency and WordSet [$F(12,32)=3.933$, $p<0.05$] such that for SetA there is a significant difference between HF (mean=3266, SE=149) and LF items (mean=3596,SE=181, $t(17)=4.11$, $p<0.001$ two-tailed pairwise comparison) and Despite mean differences between the Component (mean=3350, SE=207) and Holistic (mean=3671, SE=297) groups, there was no overall effect of Training Method ($p>0.05$).

Effects of Transfer for Holistic Training

We tested the competing hypotheses that: a) holistic learning would result in failure to acquire the alphabetic knowledge necessary to decode novel words, or b) that the code would be derived implicitly in the holistic learning condition as reflected in recognition accuracy and response time data. Two subsets of the holistic training group appear to support each hypothesis, that is, a high performing subset appear to have learned the code whereas the low performing set appear to have limited knowledge of the alphabetic code. We tested whether these groups differed in their acquisition of the alphabetic principle of the writing systems by comparing transfer performance on novel words. A repeated measures ANOVA was employed for recognition accuracy with Skill as a between-subjects factor revealing a substantial main effect of Skill level, $F(1,8)=51.80$ $p<0.001$, with high skill subjects performing at ceiling (0.91) and low skill subjects performing no better than chance (0.30). Figure 7(A-B) displays the mean accuracy as a function of WordSet for the high (royal blue) and low (light blue) skill groups within the Holistic training condition. The results of these analyses revealed no effects of WordSet or interaction with WordSet and Skill.

When we employed these same statistical tests for skill differences in recognition response times, we found that there were surprisingly no effects of Skill level or interactions WordSet. While the mean data (displayed in Figure 7C-D) appear to reflect strong differences between these groups (HS mean=4597ms compared to LS mean=5441ms), the error variance due to low numbers of observations (HS SE=171ms and LS SE=713ms) obscures any possible effects which may be evident.

Effects of Retention in Holistic Training

We tested the hypothesis that high and low performing subsets of the holistic group differ in their acquisition of the letter-sound code by comparing performance on word form retention. We argued that learning of this code results in better acquisition of word form knowledge because redundant mechanisms of word identification are enabled. Thus, we predict that the high skill group should perform faster and more accurately than the low skill group on recently trained words. A repeated measures ANOVA was employed for recognition accuracy with Skill as a between-subjects factor revealing a main effect of Skill level, $F(1,8)=33.90$ $p<0.001$, with high skill participants outperforming the low skill components, 0.93 compared to 0.60. These data are displayed in Figure 8A-B.

Tests comparing the effect of skill level on mean recognition decision times revealed no main effect of Skill or interactions. Again the predicted patterns were revealed in the differences between the means of the high performing (mean=4123ms) and low performing (mean=4732ms) subsets. However, high variance (SE=513ms and 427ms for HS and LS respectively) precluded a statistically significant effect. Means for the RT data for all groups are plotted in Figure 8C-D.

Effects of Frequency on Holistic Training Performance

A repeated-measures ANOVA for proportion correct was run on the subset of this data to compare the differences between skill within the Holistic group. As shown in Figure 9, there was a main effect of skill [$F(1,8)=5.73$, $p<0.05$]. Interestingly, the High Skill participants actually performed slower (mean=4165ms, SE=348) than Low Skill participants (mean=3021, SE=349) overall. This test also revealed a significant effect for WordSet [$F(2,8)=4.75$, $p<0.05$] with participants performing more slowly on Set C items (mean=3804ms, SE=295) compared to SetB (mean=3527ms, SE=270, $p=0.05$) and SetA (mean=3447ms, SE=194, $p<0.05$) in pairwise comparisons. An interaction between WordSet and Skill level was found to be marginally significant [$F(2,16)=3.39$, $p=0.06$]. Response time latencies increased as a function of WordSet, which reflect increasing numbers of exposures, for High skill participants (SetA: mean=3878ms, SE=274; SetB: mean=4068ms, SE=381; and SetC: mean=4548ms, SE=417), whereas Low skill participants showed no change (means=3015, 2986, and 3060ms for Sets A, B, and C respectively). There was no overall effect of frequency but a marginal interaction between frequency and WordSet [$F(2,16)=3.36$, $p=0.06$] such that for SetA there is a significant difference between HF (mean=3285, SE=164) and LF items (mean=3608, SE=228, t(9)=3.59, p<0.01 two-tailed pairwise comparison).

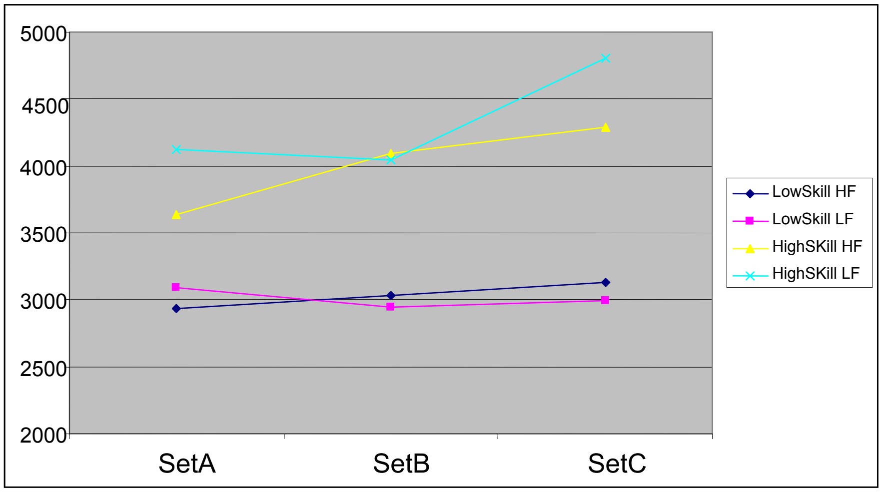

Figure 9. The effect of frequency on mean response times for the Recognition Task are shown for High and Low skilled readers within the Holistic Training Group are shown for Word Sets A, B, and C. Compared to Low skilled performers, High skilled performers show overall slower response times and a moderate effect of frequency; whereas the Low skilled performers show no effects of frequency even across Word Sets.

Novel & Pseudoword Assessments

At Session 5, participants were assessed on their ability to decode Novel Words and pronounceable Pseudowords in a Read Aloud/Identification task similar to that for trained words. We conducted several mean comparisons to test the effect of Training Method and a second set of comparisons to the effect of Skill within the Holistic group. According to our hypotheses, explicit training of letter-sound component should result in more accurate decoding of novel and pseudowords compared with holistic training. In the Novel words task, the Component group was significantly more accurate (mean=0.96, SE=0.02) than the Holistic group (mean=0.67, SE=0.12) [t(16)=2.33, p<0.05, two-tailed independent samples] (see Figure 10A). Similar results were shown for the Pseudoword task with the Component group (mean=0.97, SE=0.01) outperforming the Holistic group (mean=0.71, SE=0.12) [t(16)=2.02, p<0.05, one-tailed independent samples] (See Figure 10B).

We tested our predictions regarding the ability of participants in the holistic group to derive the letter-sound structures of the language and enable decoding of novel and pseudowords. The results were largely the same as previous tasks. The HS (mean=0.96, SE=0.04) group significantly outperformed the LS group (mean=0.37, SE=0.15) [t(8)=4.37, p<0.005, two-tailed independent samples]. Results of the Pseudoword task showed a significant difference between the high performers (mean=0.98, SE=0.01) and the low performers (mean=0.44, SE=0.17) [t(8)=3.07, p<0.05, two-tailed independent samples] within the holistic training condition.

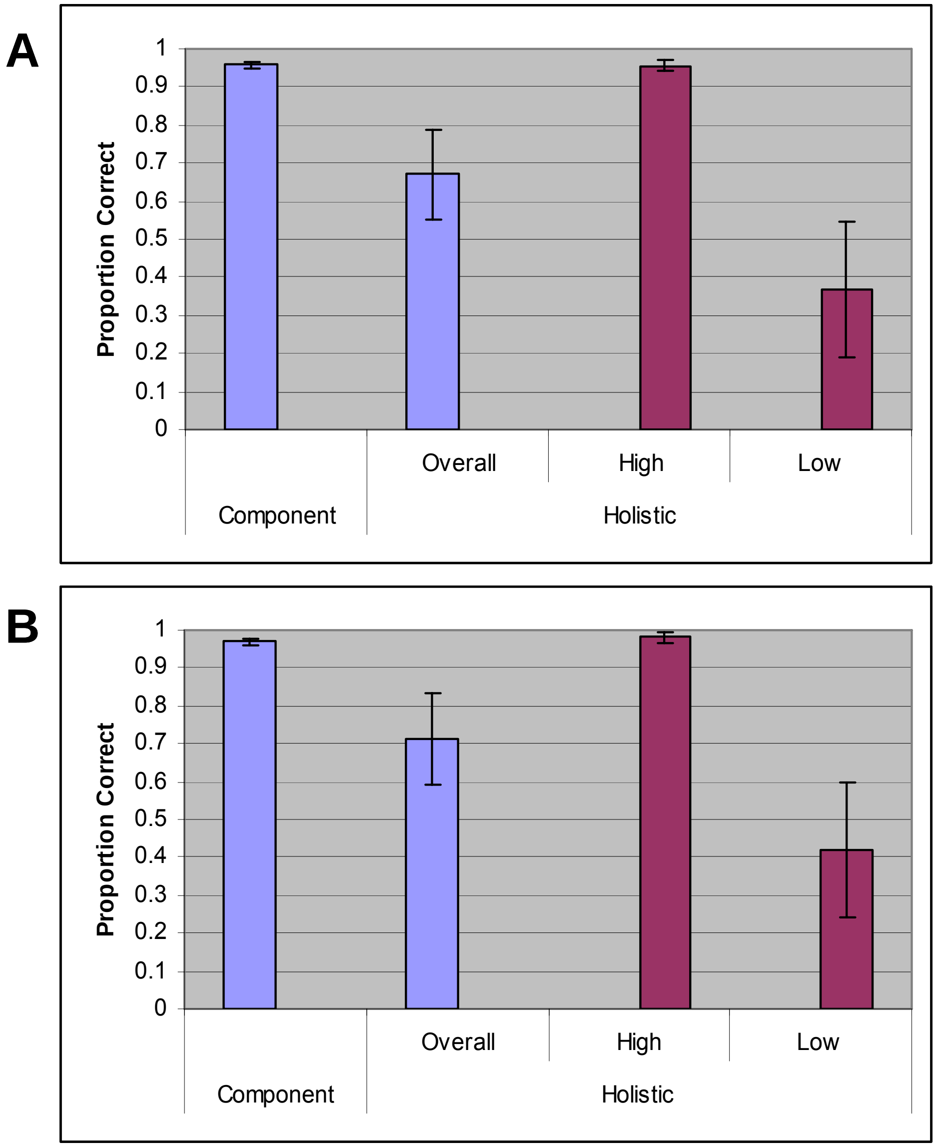

Figure 10. Identification accuracy comparing Component and Holistic and Skill groups for Novel words (A) and Pseudowords (B) that were administered in Session 5. Comparisons of the overall training conditions are shown by the blue bars on the left. Comparisons of the skill groups within the holistic condition are shown on the right by the red bars.

Exit Interviews

In the Exit Interviews, participants were asked to draw the 12 "symbols" corresponding to the visual components of which the Hangul words were composed. They were also asked to provide the appropriate sound for each symbol. These symbols or graphemes were scored as correct if they basically resembled the general visual features of the target forms. The corresponding Sounds were scored as correct only if they were matched with the correct grapheme.

Comparisons across Training Method enabled us to directly assess the degree to which the graphemes and the corresponding phonemes were acquired by the participants in including the Control group were conducted via a series of independent samples T-tests. As shown in Figure 11, the resulting means for accuracy (proportion correct) on the Symbol generation task for the Component, Holistic, and Control groups were 0.91 (SE=0.03), 0.73 (SE=0.11), and 0.34 (SE=0.13). Comparisons revealed no reliable difference between Component and Holistic groups ($p=0.09$), but significant differences between Component and Control groups [$t(16)=3.67$, $p<0.005$, two-tailed] and between Holistic and Control groups [$t(18)=2.17$, $p<0.05$, two-tailed]. Because the Sound task is dependent on Symbol performance, the results of these comparisons are nearly identical to the previous task. Mean proportions for accuracy (shown in Figure 11) on the Sound task for three training groups are 0.91, 0.70, and 0.32 for Component, Holistic and Control (SEs=0.03, 0.12, and 0.13 respectively). Again, independent sample comparisons reveal no difference between Component and Holistic groups ($p=0.08$), but reliable differences between Component and Control [$t(16)=3.98$, $p<0.001$, two-tailed] and between Holistic and Control [$t(18)=2.14$, $p<0.05$, two-tailed].

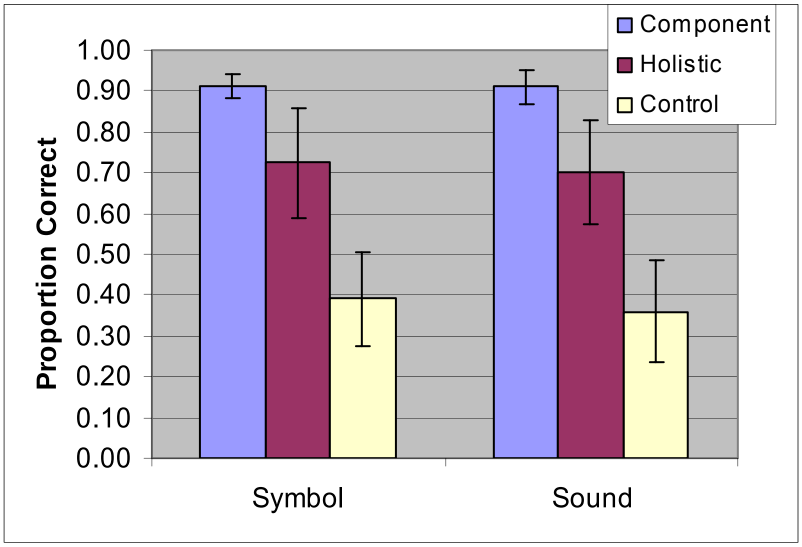

Figure 11. Accuracy on Exit Interview Symbol and Sound tasks comparing Component and Holistic and Control groups.

We subsequently made predictions regarding the ability to acquire letter-sound knowledge implicitly from the holistic training condition. We argued that holistic training could lead to logographic reading performance in which participants map visual to phonological word forms without awareness of sublexical patterns. We argue that a subset of the participants in the holistic condition do, in fact, fit this criterion. These individuals show limited ability to generalize information from learned items to novel items and poor retention of learned items. We contend that, compared to their higher performing counterparts, these readers have failed to sufficiently acquire the letter-sound code. This prediction was directly tested by comparing mean accuracies for High and Low skill subjects on the Symbol task. The high performing subjects identified on average 97% of the symbols accurately (SE=0.02) whereas the low performing group identified only 48% (SE=0.17) resulting in significant difference [$t(8)=2.80$, $p<0.05$, two-tailed]. Similarly, the mean accuracies of the Sound task are 0.97 and 0.43 for the High and Low skill groups (SEs=0.02 and 0.19) yielding a significant difference between groups [$t(8)=2.86$, $p<0.05$, two-tailed]. Thus, the set of low skill participants in the holistic training identified less than half of the 12 letter-sound correspondences in the writing system. Given that they were trained on 80 word items, it is arguable that these readers invoked logographic strategies to learn to read the trained items.

Word Decoding Skill

Raw scores on the Woodcock-Johnson WordAttack Pseudoword battery were compiled for each subject. Comparisons across groups revealed a significant difference in decoding ability between the Component group (mean=38.9, SE=1.75) and the Holistic group (mean=43.0, SE=0.75) [$t(16)=2.40$, $p<0.05$]. However, neither the Holistic nor the Component group differed from the Control group (mean=41.6, SE=1.81).

Overall performance scores for each subject in the Holistic and Component groups were computed by averaging the final two test periods (Session4 Test3 and Session5 Test1) for the dependent measures of WordID Accuracy, Recognition Task Accuracy, and Recognition Task Response Time. Performance scores for the Symbol and Sound task of the Exit Interview and the Novel Word and Pseudoword accuracy measures were tabulated to compute subsequent correlations with decoding ability. A correlation matrix was computed to determine whether decoding ability predicted subsequent performance on the dependent measures for participants in the main Training condition (excluding Control group). No significant correlations were observed. The highest correlations occurred for accuracy on the Recognition task ($r=0.27$, $p=0.23$) and response time on the same task ($r=0.19$, $p=0.62$). Thus, decoding ability in the native orthography was not a significant predictor of overall performance.

We computed a second correlation matrix on the same measures for the Holistic subjects only. In this analysis, decoding ability significantly predicted performance on two measures and resulted in non-significant but still relatively high correlation values for other tasks. Decoding ability as measured by the raw scores on the Word Attack significantly predicted accuracy on the Word ID task (r=0.67, F(9)= 6.54, p<0.05) and accuracy on the Recognition task (r=0.68, F(9)=6.82, p<0.05). Relatively high positive correlations were observed with accuracy on the Pseudoword identification task in Korean (r=0.51), accuracy on the Novel Word identification task in Korean (r=0.48), and the Sound/Phoneme generation test of the Exit interview (r=0.48). These results suggest that the underlying ability to decode letter-sound correspondences in English are strongly related to the ability to implicitly decode these relationships in a completely novel orthographic code. We compared the Word Attack scores of the participants assigned to High and Low skill levels within the Holistic training, which was solely based on their performance on the training assessment measures, and found a significant difference between these two groups (HS mean=41.8, SE=1.07; LS mean=44.2, SE=0.37) [t(8)=2.12, p<0.05, one-tailed independent samples]. Thus, the Skill groups in our Holistic training condition were predicted by performance on the Word Attack battery.

Discussion

The primary goal of our training experiment was to determine whether explicit training of the sublexical components of alphabetic writing systems leads to more efficient word learning than a holistic word-form approach. We argued that the mechanism responsible for faster and more accurate recognition of words is the internalization of the letter-sound correspondences of the alphabetic writing system. The results of the Identification and Recognition dependent measures collected throughout training revealed that overall the component group was more accurate than the holistic group, at decoding novel words particularly in the 'transfer' comparison. These findings replicate those of McCandliss et al. (1997) as well as other training studies using novel orthography paradigms (Bitan & Karni, 2003; Jeffrey & Samuels, 1967;

Bishop, 1964) and are also consistent with studies of explicit phonics based instruction (McCandliss et al., 2003; Foorman et al., 1997; 1998).

We hypothesized that explicit training of the alphabetic coding system would enable more accurate decoding of novel words than holistic training. We argued that this is because explicit training is more reliable at enabling learners to automatize or internalize the letter-sound structures of the spoken language, whereas holistic training relies on the learners ability to derive this letter-sound knowledge implicitly which is a fundamentally more difficult task. The results of our training study found that readers in the component based training were faster and far more accurate than the holistic group at transferring knowledge from session to session and at decoding pseudowords in Session 5. Again, these finding replicate those of other novel orthography paradigms (McCandliss et al., 1997; Bishop, 1964; Bitan & Karni, 2003).

We also hypothesized that explicit component training would yield better retention of word form knowledge than holistic training. We argued that internalization of the letter-sound code enables a bootstrapping mechanism through which a reader can acquire visual word form representations. In contrast, without decoding knowledge a reader must rely on the cooccurence of a visual word form with its phonological counterpart in order to store and maintain the specific knowledge. Thus, we argue, as Share (1995), that decoding knowledge serves as a self-teaching mechanism to reliably encode novel and unfamiliar word forms. In addition, we argue that this decoding knowledge serves as a redundant mechanism with word form knowledge, in that it serves to support identification for items in which these lexical representation are weak and incomplete (Perfetti, 1992). In terms of our investigation, we predicted that retention of word knowledge would be greater for the component group for precisely these reasons; the internalized letter sound code enables redundant mechanisms to establish word representations which enable fluent reading. The outcome of our study shows that the component group does indeed perform more accurately on previously learned items. The explicitly trained component group consistently outperformed the holistic group on measures of word identification and recognition accuracy. Furthermore, at the outset of training, the component training requires more time to make recognition decisions; however, by the end of the Session 4, these participants are significantly faster than their holistically trained counterparts. On the other hand, the holistically trained group shows relatively little change in overall speed from Session 1 to 4. This change in overall recognition speed reflects the notion that the explicitly trained readers are acquiring and using word form representations as opposed to relying on their decoding knowledge with each encounter with a word. These response time findings for the component group are consistent with those of McCandliss et al. (1997), who found shorter latencies in a slightly different paired match-to-sample recognition task, and Bitan & Karni (2003), who found decreases in RT for a nearly identical task. Performance of the holistic condition varies across these studies, whereas Bitan & Karni (2003) find improvement in speed of performance for the holistic/implicit group as well, McCandliss et al found increases in RT on subsequent sessions and our study finds no change across sessions. These variations are likely due to the variations in the way items were trained across subjects with Bitan & Karni repeating all stimuli, McCandliss et al repeating no stimuli, and this study repeating half of the stimuli on all subsequent trials.

We also hypothesized that component readers would be less affected by the frequency of items. We argued that the redundancy of decoding knowledge compensates for weaker word form knowledge. Perfetti (1992) argues that this mechanism can explain the frequency by regularity interaction that occurs in English. Furthermore, Frost et al (1983) show that in transparent orthographies like Serbo-Croatian, in which there are limited irregular spellings of words, there are no frequency effects since all words can be decoded. The set of letter-sound relationships in this study were completely transparent. Thus, if readers sufficiently learned the component structure of the system, there should be no effect of frequency. We found that the component group performed identically on high compared to low frequency items; whereas the holistic group showed significant differences between high and low frequency items on identification accuracy and recognition response times. This frequency manipulation has not been attempted in prior studies using novel orthographies and is the first finding using an artificial laboratory method for orthographic training.

Unlike the original study by McCandliss et al. (1997), the holistic group was not an homogeneous group. The second question that we addressed in our behavioral study was whether the underlying alphabetic structure of the writing system could be decoded implicitly from the holistic/logographic training method. The critical finding in response to this inquiry was the bimodal distribution on Word Identification accuracy in the holistic training condition which led to the subsequent skill level group differences that we analyzed in our data. Half of these subjects performed at ceiling for the transfer and retention measures suggesting that these readers have implicitly derived the letter-sound relationships of the orthography used; whereas the other half of the subjects had almost no success at decoding novel words in the four training sessions and a lack of retention for trained words, suggesting that they had little to no knowledge of the underlying alphabetic code. Direct evidence that these groups differed in knowledge of the letter-sound structure comes from the Symbol and Sound test which revealed that the high skilled group recognized on average 97% of the symbols and corresponding sounds whereas the low skilled group could only produce on average 48% of the symbols and 43% of the corresponding sounds. In comparison to the component trained group, this high skilled who have derived the code implicitly perform nearly identically on all measures of transfer and retention including response time.

High and low skilled groups also differed in terms of the effects of frequency. Low skill subjects were more accurate in identifying high frequency compared to low frequency words, whereas high skill subjects performed at ceiling for both word types. These findings confirm the hypothesis that logographic reading is more sensitive to frequency of exposure to establish quality word representations. However, decision times on the recognition task showed the opposite pattern where high skilled subjects were slower to respond to low frequency words compared to high frequency words.

It could be argued that these low skilled readers can not be characterized as logographic since they were somewhat successful at picking up on some regularities of the system. On the other hand, when we looked at the descriptions that subjects provided of the strategies used in the training phase, only 1 of the 5 described having started to attempt to decode the words via the alphabetic code. The remaining four subjects reported having noticed some regularities in the structures of the words, but not being confident in their knowledge of the exact relationships. It is crucial to take into account the fact that performance on the Word Attack pseudoword reading battery for the holistic group participants prior to training significantly predicted subsequent performance on Word Identification and Recognition accuracy in the novel orthography. In fact, there was a significant predictive difference between high and low skill readers on this measure of decoding ability with high skill readers scoring at ceiling for the task. Thus, the ability of a learning to implicitly derive the letter-sound code from holistic word training is determined by there ability to decode letter-sound correspondences in their native language. Consistent with the hypothesis of Perfetti (1992) regarding the nature of phonological coding, an underlying ability of *reflexive* phonology can determine overall skill with decomposing written forms into phonological components to better shape and refine store of print-sound correspondences. It is this *reflexive* ability which is thought to determine general reading ability and reading deficits; and in turn, the deficits exhibited in reading ability and why as discussed in our introduction explicit, systematic phonics training results in greater learning and remediation scores (Bus & Ijzendorn, 1999; Ehri et al., 2001; NRP, 2003).

The differential performance of the holistic group was not present in the study by McCandliss et al. (1997) whose orthographic stimuli was nearly impossible to parse without explicitly attending to particular features. Bitan & Karni (2003) employed a similar design in which the units representing letters were difficult to parse and thus they found that the learners in their implicitly trained condition (similar to our holistic) failed to generalize the stimuli compared to their explicitly trained group.

Theoretical Impact

As shown by Liberman et al. (1967; 1999), the ability to map graphemes to phonemes is largely dependent on individual differences in awareness of the phonological structures in the speech stream. The ability of the participants in the holistic training condition to derive the letter-sound patterns appears to be driven by individual differences in decoding ability in their native language. Previous studies have shown that the decoding ability in determined by this phonemic awareness (Sandak, unpublished dissertation). Several studies have shown that phonological analysis at the level of the phoneme is not available prior to experience with literacy training (Byrne, 1992), rather emerges later in the process of literacy development (Ehri, 1992; Ehri & Wilce, 1987). Byrne (1989) argues that compared to the syllabic awareness this level of phonemic analysis is not a natural phenomena, but emerges from the process of acquiring the alphabetic principle. According to Share (1995), children begin to utilize sublexical structural information as a bootstrapping mechanism in the development of fully specified orthographic word forms. In accordance with an "Interactive" hypothesis, these sublexical forms are acquired by constraints from both alphabetic knowledge (knowledge that each letter represents an individual sound) and from structural knowledge of the lexicon, (i.e., knowledge that lexical items in a particular language system have a particular phonetic composition).

As knowledge of these structural units increases, the computational system has greater generative power to produce and recognize an unlimited number of words. That is, a child can generate more accurate candidate word forms from the lexicon when identifying novel or familiar words. Chall (1996) claims that this knowledge of structural features expands children's abilities to recognize words and to gain fluency and speed in reading. These frameworks (Share, 1995; Perfetti, 1992; Ehri, 1992) postulate an automatic stage of word recognition; however, they vary dramatically on what that system entails. For example, Adams (1990) suggests that automaticity is achieved as a function of built-up associations among the form-based constituents (orthography and phonology) triggering recognition. "As the reader encounters more and more words, the associations between the letter units will ultimately come to reflect the more general orthographic structure of the printed language" (p. 129). Whereas Ehri (1991) concludes that all students learn to read words by sight but that there are different ways to achieve this goal dependent upon instruction.

While direct evidence for the acquisition of word-specific representations remains somewhat elusive, a number of studies have reported experimental data consistent with this hypothesis. For example, Reitsma (1983, Experiment 2) found that 2nd graders were able to discriminate previously taught pseudowords from homophonic foils after 8 exposures. Reitsma (Experiment 3) also found that skilled First graders (but not level-matched disabled readers) were able to read target spellings for recently taught words versus similar homophonic spellings. In a recent test of his *self-teaching hypothesis*, Share (1999) taught normal 2nd graders to read novel pseudowords by embedding them in short texts where meaning could be derived by context. These subjects were able to recognize and name target spellings more quickly then homophonic foils. Share (Experiments 2-4) also found that phonological recoding, but not visual presentation or contextual factors, determined the quality of the word-specific representation and subsequent performance of the child. So while exposure-frequency is important to Share's thesis, the development of access routes in terms of decoding mechanisms is fundamental.

One of the fundamental distinctions that has been made in the reading literature, especially following the publication of Perfetti's (1991) and Share's (1995) models, is that of word recognition strategies as sight-word vs. decoding based strategies. Since Coltheart's dual-route model (1978), there has been a tendency to describe word recognition as occurring via the dichotomous cognitive mechanisms of direct visual access (sans phonology) versus addressed phonology (or phonological decoding). However, researchers such as Ehri (1991, 1992), Foorman (1994), and Goswami (1990), have all supported the framework we have described which describes the relationship of orthographic and decoding knowledge as functionally interdependent with the latter serving as a *bootstrapping* mechanism for the former. This framework predicts that an influence of lexical knowledge will be secondary to that of decoding knowledge, but will subsequently increase in relation to skilled reading.

3.0 FMRI EXPERIMENT: THE EFFECTS OF TRAINING ON CORTEX

The primary aim of this experiment is to investigate cortical differences resulting from the training manipulations reported in the behavioral portion of the study. We hypothesized that Component and Holistic training would result in the reliance on separable regions of cortex. Specifically, we argued that both training methods would converge on a set of common regions associated with lexical processing of visual word forms, but that the explicit alphabetic training would rely on a set of regions associated with grapheme-phoneme processing. Based on evidence from previous studies such as Paulesu et al (2000), we predict that these regions would be localized in the left posterior superior temporal region including inferior parietal and angular gyrus.

A second aim of the behavioral study attempted to assess whether holistic lexical training would produce logographic reading behavior or if the alphabetic knowledge would be derived implicitly. The underlying goal of this attempt was to enable us to measure variations in cortex due to the differences between logographic and alphabetic orthographies as those discussed in Bolger et al. (2005). We attempted to identify patterns of logographic reading in individuals from the holistically trained group and identify variations in the cortical activity of these participants compared to those who have sufficiently learned the letter-sound components. Specifically, we compared activation in the low-skill subset of the holistic group to the high skilled and explicitly trained participants. We predict that a similar pattern as discussed earlier should emerge in which alphabetic reading, compared to logographic, should rely more heavily on the dorsal route of the STG, whereas both systems would rely on the ventral route associated with lexical processing. However, we predict that the visually demanding nature of holistic processing may elicit greater activity in the RH homologue of the VWFA and the left middle frontal gyrus as seen in studies of Chinese.

The third aim of this portion of the experiment was to uncover variations in cortical activity associated with developing reading skill. We argued that the region central to visual word form processing, the VWFA, located in the left mid fusiform region develops as a function of reading skill. Our fMRI paradigm, included a Control Group, which we described earlier in the behavioral section, that received minimal training on all 80 novel orthography words to function as a low experience control group to measure the plasticity of target cortical regions. This group was provided minimal training as opposed to serving as a naïve baseline, because our target hypothesis was that target regions of the VWFA and inferior frontal gyrus should activate as a function of skill and not just basic familiarity with the stimuli. Thus, we predict that both experimental training groups (Component and Holistic) should activate the VWFA and inferior frontal gyrus more reliably than the control group.

In the neuroimaging portion of the experiment, we examined cortical activation with fMRI of the reading network during a simple visual recognition task using various stimuli from the native English and novel Korean Hangul orthographies in the participants from the behavioral portion of the experiment following the and fifth (or only in the case of the Control group) session. We employed a 1-back visual match task in order to examine automatic activation of the network that occurs in a relatively passive recognition task. In this fMRI design, we compared cortical activation to stimuli from both the newly learned orthography and the native orthography, Roman alphabet.

In addition to our target hypotheses, we attempted to use our stimulus condition to localize particular structure-function relationships found in the literature. Our stimuli consisted of several levels of orthographic processing across the two orthographies: single letters, pseudowords, and words of low and high frequency. In the native orthography condition, we included a consonant string condition to enable localization of legal/pronounceable compared to illegal/unpronounceable letter strings. These levels in the native orthography served to enable mapping of frequency (high vs. low word items) lexicality (words vs. nonwords), legality (words and pseudowords vs. consonant strings), and orthographic length (consonant strings vs. individual letters). We also tested whether training in the novel orthography reveal the same effects of frequency and lexicality. We also tested decoding ability in the novel orthography comparing novel and pseudowords to a fixation baseline to compare differences across training groups. We argue that the cortical response to high and low frequency words will follow similarly to that of English words. That is, compared to high frequency items, low frequency words will elicit more activation in representation based regions such as the occipito-temporal and ventral inferior frontal regions. Regions of the superior temporal gyrus and dorsal inferior frontal region may show more activation as well, but given there phonological nature, these areas may interact with training performance; meaning that logographic readers may be less likely to activate these regions for high or low frequency words.

Lastly, because training results in the acquisition of skill and the induction of automaticity, we postulate that high performing subjects will show reduced activation in central executive regions including the dorsal lateral prefrontal cortex, anterior cingulate, and posterior parietal region as proposed by the CAP3 architecture Schneider & Chein (2003).

3.1 FMRI DESIGN AND METHODS

This fMRI experimental design consisted a blocked box-car design (see Chein & Schneider, 2003). Each run was composed of 11 stimulation blocks interspersed with 12 fixation blocks (runs begin with 18 seconds of fixation of which the first 6 are discarded to allow tissue to settle into a steady state). Stimulation blocks lasted 18 seconds with a single stimuli presented for 1500ms followed by a 300ms fixation (SOA = 1800ms) for a total of 10 stimuli occuring in each block. The duration of each run was approximately 6 minutes (5:48). A lag time of approximately 60 seconds between runs enabled the experimenter to instruct subjects, comment about movement, and set-up the subsequent run. The stimulus conditions included several dimension of **Native Orthography:** high frequency words, low frequency words, pronounceable pseudowords, consonant strings, and individual letters, as well as several dimension of the **Novel Orthography:** high frequency trained items, low frequency trained items, novel words, pseudowords, and individual Hangul letters. Arabic letter strings were used as a visually-based orthographic control stimulus. These eleven conditions were presented once per run composing the eleven stimulation blocks per run. The scan session for each participant consisted of seven runs resulting in 7 replications or observations for each condition.

In the fMRI boxcar stimulation design, each 18sec stimulation block was followed by a 12 sec fixation block in which subjects must press a button when the fixation point blinks. In the 1-back decision roughly 10% of stimuli were target stimuli (repeated item), resulting in about 1 repetition (target word) per stimulus block. Similar to the 1-Back stimulation blocks, the fixation blinks occurred roughly 10% of the time or about once each block.

Stimuli

The stimuli used in this fMRI design for the **Novel Orthography** conditions were created from those presented in the behavioral training part of this experiment. The single **Letter** condition was straightforward using the 12 graphemes (letters) of the Korean Hangul. The **Novel Word** and **Pseudoword** conditions consisted of the 80 (40 for each condition) CVC-structured stimuli utilized in Session5 as described above. The **High Frequency (HF-Korean)** word condition consisted of the subset of trained words from Sets A, B, and C that were presented in subsequent Sessions (for a total of 64, 48, and 32 training trials respectively); whereas the **Low Frequency (LF-Korean)** words consisted of those words from Sets A, B, and C which only presented (in terms of training trials) in their respective training Sessions (a total of 16 exposures). Thus, both HF and LF conditions consisted of 30 stimuli. Since there were 10 stimuli per block (9 unique stimuli + 1 repeated target word) and each condition repeated 7 times (once per run), words in each condition were repeated at least one time. We avoided using Set 4 stimuli in order to avoid having recency affect the cortical signal.

The **Native Orthography** stimuli are directed, in part, to be comparable to **Novel Orthography** stimuli. The sixty **High Frequency (HF-English)** and **Low Frequency (LF-English)** word stimuli were composed of 4-7 letters (to control for length) were selected from the MRC database (Coltheart, 1981). High frequency English words occurred more than 100 per million and low frequency words occurred between 1 and 10 per million (Francis & Kucera, 1982). Both HF and LF words had average concreteness and imageability rating of less than 3.0 on a 7-point scale using the MRC corpora. This was done to reduce the visualization of word referents and the related cortical activity. **Pseudoword (PW-English)** stimuli were created based on permuting 1-2 letters of the High and Low Frequency word items to create illegal but pronounceable letter strings. **Consonant String (CS)** stimuli were adapted from a set of letter strings with high bi-gram frequencies used in a prior study (Phillips, Laurent, Geudiche, Bolger, Perfetti, & Fiez, in press) and varied from 4-6 letters in length. All 26 letters in the English language were utilized in the **Letter (L-English)** condition. All native orthography stimuli were presented in 36-point Arial font. Therefore, almost all word stimuli in both frequency conditions were repeated only one time. Sixty **Arabic** letter strings 4-6 letters in length were created using legal patterns of letters created using Microsoft Word language tools. Figure 12 displays the stimulus conditions and sample stimuli used in the fMRI stimulation blocks.

Novel Orthography:

High Frequency	립 (rib)
Low Frequency	맛 (mat)
Novel Words	빕 (bib)
Pseudowords	빔 (bim)
Individual Letters	ㅂ (b)

Native Orthography:

High Frequency	**buy**
Low Frequency	**hue**
Pseudowords	**bilp**
Consonant Strings	**lrfr**
Individual Letters	**R**

Control

Arabic	فغب

Figure 12. Stimulus Conditions presented in the 1-back task presented in a blocked fMRI design. Samples of the Novel Orthography Korean stimulus conditions are shown on the left, of the Native Orthography English stimulus conditions on the right, and of the Arabic Control stimuli on the bottom.

fMRI data acquisition

The imaging portion of this experiment was run at the Univeristy of Pittsburgh's Brain Imaging Research Center (BIRC) on the 3-Tesla (Siemens Allegra) scanner. Functional images were collected with a T2* weighted gradient-echo EPI sequence (TR = 2000ms, TE = 35m) with 34 axial slices at 3.0mm (skip 0) starting at the base of the temporal pole for nearly whole-brain coverage. A 34 slice oblique-axial structural series was acquired, collected parallel to the AC-PC plane with a standard T1-weighted spin-echo pulse sequence (TE = 12 ms, TR = 500 ms, FOV = 210, slice thickness = 3.0 skip 0), as an "in-plane" anatomical reference. The functional series were acquired in the same plane as the structural series. Lastly, we acquired a high-resolution (256x256; FOV 110) 3D structural image (Seimens MPRAGE) with voxel size equal to 1mm for acute ROI analysis of functional data.

fMRI Data Analysis

Analyses were conducted off-line using the NeuroImaging Software package 3.5 (developed at the University of Pittsburgh and Princeton University, Fissel et al., 2003), BrainVoyager, and SPM. Images were corrected for subject motion using a 6-parameter rigid-body automated registration algorithm, and were linearly detrended. To form a group composite, the structural images collected from each subject were co-registered to a common reference anatomy using a 12-parameter affine transformation algorithm. Functional images were transformed into common space. The statistical maps resulting from each analysis were transformed into stereotaxic space (Talairach and Tournoux, 1988) for final reporting.

Analyses of the fMRI data were conducted using voxel-based statistical techniques. Each analysis employed a random effects model, wherein subject was treated as a random factor. All initial statistical tests were subjected to a False Discovery Rate (FDR) corrected alpha of 0.05, and a clustering criterion of six contiguous active $3mm^3$ voxels.

3.2 FMRI RESULTS

The functional data were analyzed using a least squares estimate general linear model (GLM) approach which accounts for the temporal shift of the fMRI BOLD signal as a function of the model predictors (see Zarahn, Aguirre, & D'Esposito, 1999). The full model included the eleven stimulation conditions (shown in Figure 11) plus the fixation control condition. The predictors of the conditions were modeled using a standard deconvolution algorithm of the hemodynamic response (Boynton, Engel, Glover, & Heeger, 1996) with a double gamma function time-locked to the onset of the stimulation block. We report several analyses based on this full model: a) the activation of the network involved in the native orthography, b) the activation of this native region by the novel orthography, and c) the contrast of regions activated by the novel compared to native orthography. In order to directly test the effects of training, we conducted a set of three group-based ANCOVA analyses with subject as a random factor for 2-way comparisons between 1) Component and Holistic groups, 2) Component and Control groups, and 3) Holistic and Control groups. The critical analysis to test the hypotheses regarding Lastly, we conducted a random effects ANCOVA model on the 10 participants in the Holistic group to assess the covariance of performance on the Word Identification task (accuracy) with the cortical activation associated with processing trained Korean orthography conditions.

Native Orthography Reading Network

The first goal of our analysis was to localize the network of regions supporting word recognition in the native orthography (English). In order to achieve this, an activation map was obtained from the contrast of all English stimuli conditions (HF-E, LF-E, PW-E CS-E, and Letters) with the fixation blink condition. This test resulted in large clusters of activation in predictable regions across cortex at an FDR corrected alpha level of 0.05. Regions of interest (ROIs) were localized within these clusters using a watershed algorithm (FIDL) which identified unique clusters surrounding a peak voxel. To achieve this, a cortical mask was created for all voxels above the stated statistical threshold (FDR: q=0.05). By gradually reducing the statistical threshold from the highest to lowest statistical value, individual peaks are identified and ROIs are drawn that include all voxels (of lesser value) in the mask (thus above the overall threshold) within a predefined 10mm radius of the peak. To insure unique regions, peaks occurring within a 10mm radius of each other are merged according to voxel of highest value. This procedure resulted in 29 regions of interest which are detailed in Table 2.

Activation of these regions was assessed using random effect GLMs for each of the 29 ROIs with planned contrasts for each of the five English conditions as well as the Arabic Control condition compared to the fixation control task—Novel orthography conditions were also assessed in the same test and are reported in the following section. The results of these tests are reported in Table 2. Several regions in the ventral visual stream from cuneus to inferior occipital and inferior temporal were significant for all stimulus conditions. These include the bilateral regions in the mid fusiform gyri (BA37), the mid and inferior occipital gyri (BA18/19), and cuneus (BA17) as well as regions in left parahippocampal gyrus (BA19). Anterior regions of the right fusiform gyri extended medially (x=27, BA 20) compared to the left fusiform activation (x=-37). Several regions of the superior and middle temporal gyri bilaterally were strongly activated for LF-E condition and moderately for PS-E and HF-E conditions. However, Consonant String and Letter stimuli failed to activate right hemisphere regions and, in general, only weakly activated regions in the left hemisphere. The control (Arabic) stimuli failed to activate any these regions. The only other posterior region which fell into this criterion was the left angular gyrus (BA39) which was significantly active for all conditions. Moving anteriorly, regions in the left frontal cortex were found including several peaks in precentral gyrus (BA4/6), inferior frontal gyrus (BA9 and BA13), as well as a region in medial frontal gyrus (BA6) and insular cortex (BA13). Regions of the precentral gyrus were largely active for all stimulus conditions with the exception of the most anterior region which showed no activation for Letters and weak activation for HF-E items. The two inferior frontal regions were activated for all English stimuli except for Letters, and the anterior portion failed to activate for Arabic stimuli. The medial frontal region also elicited activation to all English and Arabic control stimuli as well. Two additional regions of interest include: a) the left Lentiform nucleus, which activated for LF-E, PW-E, CS-E stimuli, weakly for HF-E and Arabic stimuli, and not at all for Letters, and b) the right Anterior Cingulate (BA32) which activated for the LF-E and PS-E stimuli only.

Table 2. Activations of Regions of Interest for the Native Orthography reading network by Stimulus Condition in both Native and Novel Orthographies

Region	*x*	*y*	*z*	Arabic	English HFWords	LFWords	CString	Pseudo	Letter	Korean HFWord	LFWord	Novel	Pseudo	Letter
L fusiform gyrus (BA37)	-37	-42	-18	9.34	10.52	7.59	10.87	7.35	4.11	7.75	6.44	7.05	7.56	7.77
L fusiform gyrus (BA37)	-43	-50	-20	7.23	7.40	6.29	8.33	6.31	5.47	11.18	10.68	6.99	9.58	8.91
L fusiform gyrus (BA37)	-39	-55	-14	15.24	7.79	8.26	10.56	6.25	7.44	11.62	10.72	9.11	10.72	10.13
L Parahippocampal gyrus	-40	-43	-7	5.66	6.40	5.28	6.18	3.20	3.50	4.68	4.92	4.07	3.43	4.67
L Parahippocampal gyrus	-39	69	-9	12.59	8.76	7.63	9.56	7.84	7.91	10.82	11.51	10.17	11.61	10.56
L Post fusiform (BA19)	-35	-80	-17	8.21	8.74	8.50	8.11	7.30	5.10	7.83	8.33	6.98	9.02	6.13
L inf occip gyrus (BA18)	-25	-86	-12	9.78	11.97	12.02	12.15	11.05	7.14	12.89	11.10	9.15	10.73	8.48
R fusiform (BA20)	27	-38	-17	10.85	5.71	4.39	7.14	6.43	3.95	8.31	5.90	8.20	6.50	7.01
R fusiform (BA37)	35	-56	-15	11.41	7.66	6.05	9.78	7.83	6.71	12.65	11.66	11.90	11.81	11.73
R inf occip gyrus (BA19)	39	-72	-9	12.07	8.86	6.49	9.49	6.36	7.57	10.38	11.06	9.86	10.13	13.02
R mid occip gyrus (BA18)	30	-82	-9	10.61	9.82	8.05	10.88	8.64	7.49	11.19	9.48	10.52	10.15	11.75
R cuneus (BA17)	22	-91	-1	10.49	11.22	9.27	8.37	9.10	5.47	12.04	12.51	10.39	10.76	8.32
L SPTG (BA22)	-56	-41	7	-	7.20	3.57	3.47	3.81	-	-	-	-	-	-
L mid temporal gyrus	-56	-32	2	-	6.80	3.50	-	3.36	-	-	-	-	-	-
L sup temporal gyrus (BA21)	-56	-19	1	-	5.13	3.12	-	3.04	-	-	-	-	-	-
L sup temporal gyrus (BA39)	-46	-46	11	-	7.04	2.58	2.44	2.78	-	-	-	-	-	-
L angular gyrus (BA39)	-26	-61	32	5.68	5.27	2.95	7.04	4.69	4.55	7.21	7.06	8.21	7.37	8.48
R sup temporal gyrus	50	-30	6	-	7.45	-	-	2.79	-	-	-	-	-	-
R sup temporal gyrus	48	-21	4	-	5.39	-	-	2.83	-	-	-	-	-	-
L precentral gyrus (BA4)	-51	-12	41	4.66	6.04	4.45	7.93	7.14	5.89	5.01	5.78	5.54	6.37	6.72
L precentral gyrus (BA6)	-46	1	34	6.26	7.34	4.35	6.99	6.35	4.20	6.79	6.99	5.64	5.65	7.10
L precentral gyrus (BA6)	38	6	1	4.70	5.11	3.31	6.76	5.31	3.99	5.47	6.03	5.50	5.58	6.44
L precentral gyrus (BA6)	34		3	3.89	5.16	2.56	4.49	4.31	-	4.29	3.97	2.91	3.20	4.53
L inf frontal gyrus (BA9)	47		3	4.03	5.31	3.76	3.51	5.35	-	3.37	3.57	2.99	3.39	3.99
L inf frontal gyrus (BA13)	45	3		-	4.28	3.70	4.97	4.23	-	2.66	2.73	2.18	2.73	-
L insula (BA13)	27	8		5.46	4.27	-	4.78	4.06	2.91	5.50	7.27	4.81	5.91	4.97
L medial frontal (BA6)	7	3	4	5.53	6.02	2.85	6.36	6.30	4.65	6.96	6.66	6.58	6.51	6.73
R ant cingulate (BA32)	0	4	1	-	4.46	-	-	3.24	-	-	2.82	-	-	-
Lentiform (BA)	26			2.80	4.24	2.31	4.42	3.81	-	5.14	5.21	3.81	3.92	4.71

Effects of Novel Orthography

The effects of the various Novel Orthography conditions on the regions of the native reading network (as determined above) across all subjects were assessed using random-effects GLMs for each of the 29 ROIs described above. As for the native orthography stimuli, the regions of the ventral visual processing stream activated strongly for all stimulus conditions. The superior temporal regions did not show reliable activations for any of the Novel orthography conditions; however, as was the case for the previous conditions, the angular gyrus was active above fixation for all conditions. Regions in left Frontal cortex were also active for all conditions with the sole exception of the anterior IFG (BA13) which failed to activate for the Korean Letter condition similar to the finding for English letters. The left Lentiform nucleus was also active for all conditions, whereas the right Anterior Cingulate (BA32) was only active for the LF-K condition, again similar to the finding for English.

Direct Comparison of Native vs. Novel Orthography

To better understand the overall difference between Native and Novel orthographies, we directly compared the (known) word conditions in the English and Korean stimuli (HF and LF). We conducted a planned comparison of Korean over English stimuli which revealed a series of bilateral regions in ventral visual cortex including: Middle Occipital, Fusiform, Precuneus, and Cuneus as well as frontal regions including the Precentral gyrus and Insula bilaterally and importantly left middle frontal gyrus. Those regions that were more active for English than Korean stimuli include: bilateral superior temporal gyrus (BA22), right precentral gyrus, and left middle temporal gyrus and left anterior cingulate.

Table 3. Contrasts of cortical activation for Novel and Native Orthography words

Region	BA	*x*	*y*	*z*	*T*
Korean vs. English					
Middle Occipital Gyrus	BA 37	-46	-66	-6	7.34
Middle Occipital Gyrus	BA 18	-31	-84	5	4.50
Fusiform Gyrus	BA 37	38	-59	-10	9.18
Fusiform Gyrus	BA 37	25	-50	-10	8.35
Middle Occipital Gyrus	BA 18	30	-82	5	8.66
Inferior Parietal Lobule	BA 40	-35	-53	39	8.08
Superior Parietal Lobule	BA 7	30	-53	43	8.10
Precuneus	BA 7	-24	-70	40	8.25
Precuneus	BA 7	21	-70	41	8.59
Cuneus	BA 18	-24	-78	23	7.21
Precuneus	BA 31	25	-74	25	8.25
Insula	BA 13	32	18	7	6.14
Insula	BA 13	-32	18	7	4.36
Precentral Gyrus	BA 6	-47	-5	39	5.02
Precentral Gyrus	BA 6	41	2	34	4.77
Middle Frontal Gyrus	BA 9	-46	19	33	4.41
English vs. Korean					
Precentral Gyrus	BA 43	51	-6	14	5.33
Superior Temporal Gyrus	BA 22	51	-5	-5	6.24
Middle Temporal Gyrus	BA 21	-53	-13	-6	5.62
Middle Temporal Gyrus	BA 22	-54	-38	3	4.81
Superior Temporal Gyrus	BA 22	-53	-9	7	4.10
Anterior Cingulate	BA 24	-2	34	-2	5.97

Group Comparisons

A series of three 2-way group effect ANCOVA models tested the differences between the two experimental training groups and the control group on the five Novel orthography stimulus conditions. Because the data from these comparisons could not meet the stringent FDR corrected alpha level of 0.05, we set the cluster threshold to 180mm (or 20voxels) and the p-value to 0.001 to find regions of interest. Comparing the primary experimental groups to one another revealed only a small set of regions meeting our criterion that were more active for the Component than the Holistic group: the right inferior parietal lobule (BA40), the right superior frontal gyrus (BA 9), and the left superior posterior temporal gyrus (BA22). There were no regions more active for Holistic compared to the component group. The contrast of the Component group to the Control group revealed several regions including the right insula (BA22), cuneus (BA18), and the left precentral gyrus (BA 4/6). Two mid brain regions were also found for this comparison including the left thalamus and the substantia nigra.

Table 4. Resulting cortical activations for comparisons of Training Conditions

Region	**BA**	***x***	***y***	***z***	***T***	**Voxels**
Component vs. Holistic					*t(17)*	
Inferior Parietal Lobule	BA 40	41	-50	36	-4.87	954
Superior Frontal Gyrus	BA 9	12	55	30	-3.74	183
Superior Temporal Gyrus	BA 22	-33	-48	26	-4.76	377
Component vs. Control					*t(17)*	
Insula	BA 22	43	-31	-4	4.68	622
Cuneus	BA 18	6	-76	28	4.27	261
Substania Nigra		-5	-16	-9	4.65	266
Thalamus		-12	-17	6	4.64	898
Precentral Gyrus	BA 6	-44	-10	26	4.90	433
Precentral Gyrus	BA 4	-59	-5	18	4.39	330
Holistic vs. Control					*t(19)*	
Inferior Parietal Lobule	BA 40	60	-30	37	5.13	568
Superior Frontal Gyrus	BA 6	12	15	52	5.30	194
Cingulate Gyrus	BA 31	-19	-29	42	4.33	155
Inferior Parietal Lobule	BA 40	-45	-58	36	5.11	1259
Inferior Parietal Lobule	BA 40	-58	-48	41	4.58	195

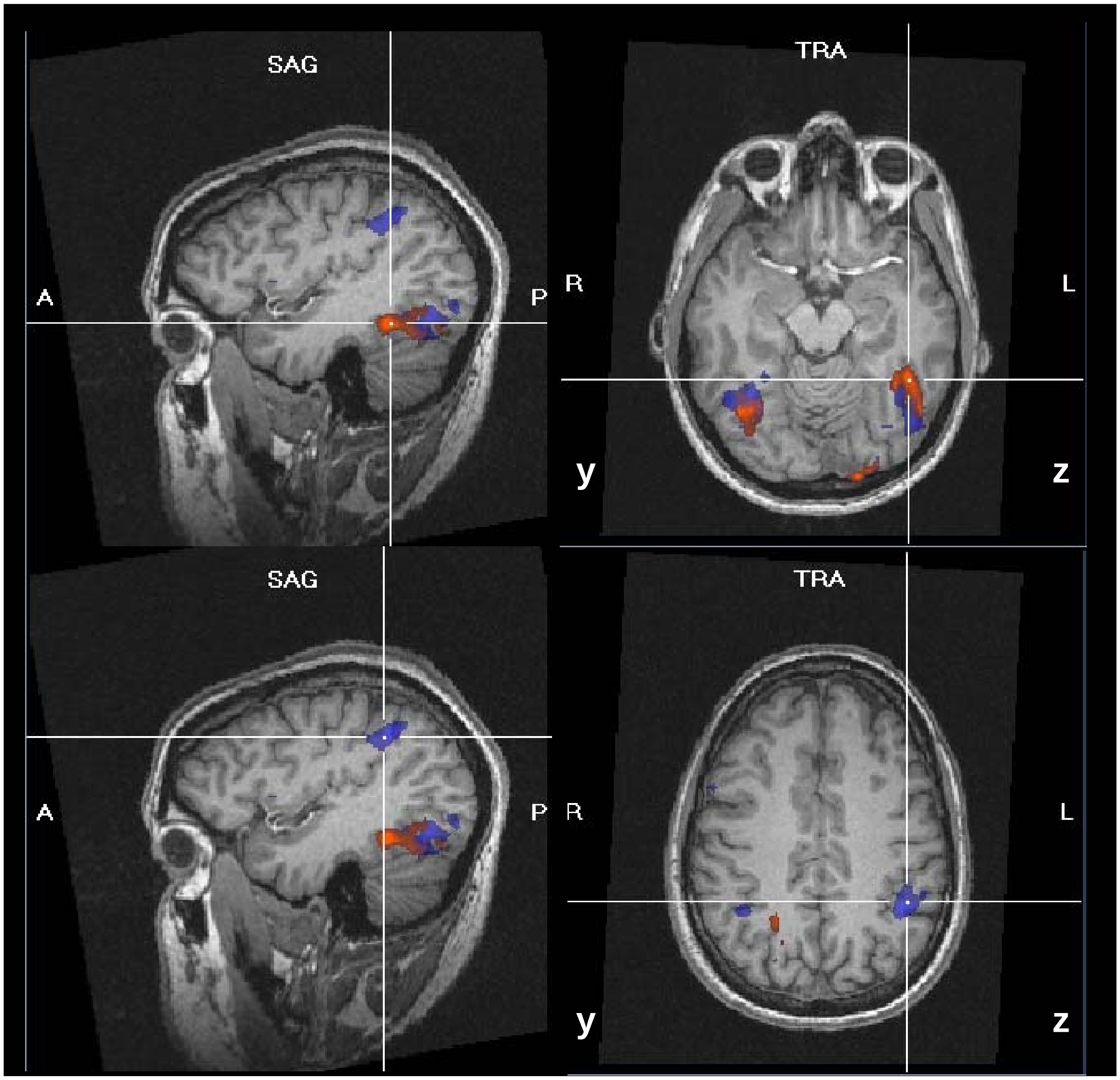

Figure 13. Activation maps for Trained Korean word stimuli (HF-K+LF-K > Fix) for the Holistic Training Group (Red) and the Component Training Group (Blue). The top row show activation in the left putative word form region in the sagital slice (top left). The axial slice (top right) shows activation in the bilatereal (left hemisphere is shown on right) inferior occipital-temporal boundary region including the mid-fusiform VWFA in the crosshairs. The bottom row shows activation in the left inferior parietal lobe activated for the Component Group in the sagital slice (bottom left) and in the axial slice (bottom right) in which the right hemisphere homologue can be seen.

ROI Based Analyses of Experimental Groups

The fundamental goal of the fMRI experiment was to isolate regions of the "reading network" or the set of regions commonly activated across tasks of visual word recognition (Bolger et al., 2005; Fiez & Petersen, 1998; Jobard et al., 2003). Our goal was to uncover the differential activation in these regions for the Component and Holistic training conditions. For this analysis, we subdivided the Holistic training condition into High and Low performing groups to compare the cortical effects of logographic reading (the Low performing groups failure to derive letter-sound code sufficiently), deriving the letter-sound code implicitly (the High performing group), and the explicitly trained group (Component condition).

In order to identify these region, we used a data-driven method of isolating ROIs. From the overall random-effects GLM model, an activation map was created from the contrast of all orthographic conditions compared to the fixation baseline condition with an FDR corrected alpha of 0.01. We isolated individual ROIs from the resulting map by employing the watershed methodology described earlier. Again, individual peaks occurring within 10mm were merged and extents of the ROIs were drawn at a radius of 10mm from peaks. Excluding regions occurring in white matter and medial regions of the brainstem and cerebellum, a total of 36 ROIs were found in regions commonly discussed as part of the reading network: ventral occipito-temporal, superior posterior temporal regions including inferior and superior parietal areas, and inferior frontal regions including precentral gyrus, insula, and middle frontal cortex. While these regions have been commonly found in the left hemisphere, based on the data from our activation maps, we included right hemisphere homologues of these classical. We also included regions of the cingulate cortex, particularly the anterior cingulate gyrus, that are associated with executive functioning (Chein & Schneider, 2003). After isolating the ROIs, we conducted random-effects GLMs on each ROI with planned contrasts comparing each of the novel Korean orthography conditions (HF words, LF words, Novel words, Pseudowords, and Letters) to the fixation baseline for the Component training condition, and the High and Low performing Holistic groups.

The results of these analyses are displayed in Table 5. The component training condition activated all target regions for most conditions with the exception of the ventral aspect of the precentral and middle frontal gyri, which failed to activate for novel and pseudoword reading. Both the component and high skill holistic readers activated the anterior cingulate for high frequency words only. In comparison to the component training group, high skilled holistic performers activated much of the reading network for both low and high frequency items as well as novel and pseudoword items with the exception of the bilateral insula regions and which were only active for high frequency items. On the other hand, low skilled responded to high but not low frequency items including the left anterior fusiform (BA37), right inferior and superior parietal regions (BA40/7), and left precentral (BA6) and middle frontal regions (BA9).

Table 5. Performance Groups activations for Korean Stimulus Conditions in ROIs derived from both Native and Novel orthographies.

					Holistic Low					***Holistic High***					***Component***				
Region	***x***	***y***	***z***	**#Vxls**	**HF**	**LF**	**Nov**	**Psd**	**Lett**	**HF**	**LF**	**Nov**	**Psd**	**Lett**	**HF**	**LF**	**Nov**	**Psd**	**Lett**
L Inf Occipital G (BA18)	-38	-86	-8	2325	2.15*	2.36*	2.17*	2.11*	2.21*	***1.89***	2.17*	2.08*	2.04*	***1.95***	3.06**	2.72*	3.00**	2.87*	3.02**
L Post Fusiform G (BA18)	-21	-88	-18	1641	2.07*	2.10*	***1.95***	***1.96***	***1.94***	2.31*	2.34*	2.35*	2.34*	2.14	2.48*	2.02*	***1.96***	2.22*	2.37*
L Post Fusiform G (BA18)	-31	-85	-17	1928	2.20*	2.33*	2.16*	2.17*	2.18*	2.24*	2.31*	2.30*	2.29*	2.14	2.80*	2.27*	2.46*	2.69*	2.64*
R Post Fusiform G (BA19)	23	-83	-16	2415	-	-	-	-	2.07*	2.34*	2.35*	2.25*	2.16*	2.00	2.56*	2.23*	2.30*	2.44*	2.59*
R Fusiform G (BA19)	35	-75	-9	3762	2.17*	2.05*	2.24*	2.22*	2.40*	2.08*	2.16*	2.03*	2.01*	2.29	2.87*	2.82*	2.87*	2.81*	2.96*
L Fusiform G (BA19)	-39	-73	-12	3191	***1.90***	2.11*	-	2.17*	2.10*	***1.93***	2.09*	2.06*	***1.98***	***1.95***	3.04**	2.78*	2.94*	3.08**	2.97*
L Fusiform G (BA37)	-44	-63	-10	3346	2.07*	2.16*	***1.92***	2.15*	2.09*	2.22*	2.29*	2.30*	2.19*	***1.99***	3.09**	3.15**	3.10**	3.15**	3.10**
R Fusiform G (BA37)	38	-60	-12	3723	2.35*	***1.94***	2.27*	2.19*	2.38*	2.27*	2.38*	2.31*	2.15*	2.18	3.06**	3.13**	3.12**	3.14**	3.09*
L Fusiform G (BA37)	-39	-52	-18	3907	2.04*	-	***1.93***	2.27*	2.23*	2.11*	2.10*	2.05*	-	-	3.06**	2.99*	2.94*	2.79*	2.99*
R Fusiform G (BA20)	30	-41	-18	2460	-	-	-	-	-	2.33*	***1.92***	-	-	-	3.03**	3.16**	3.02**	2.87*	2.97*
R Parahippocampal G (BA36)	23	-34	-19	550	-	-	-	2.06*	2.28*	2.05*	-	-	-	-	2.63*	2.44*	2.49*	-	2.73*
R Inf Parietal Lob (BA40)	33	-53	43	2459	2.04*	-	***1.95***	-	2.00*	2.09*	2.28*	***1.93***	***1.91***	2.17	2.51*	2.77*	2.55*	2.53*	2.40*
L Inf Parietal Lob (BA40)	-36	-50	38	3397	-	-	-	-	2.03*	-	2.33*	2.19*	-	-	3.01**	2.99*	3.01**	2.70*	3.06**
L Inf Parietal Lob (BA40)	-46	-42	39	2449	-	-	-	-	***1.91***	-	-	-	-	-	2.98*	3.00**	3.02**	2.70*	3.06**
R Inf Parietal Lob (BA40)	40	-42	40	1599	2.02*	-	-	-	-	2.14*	-	-	-	-	2.39*	3.08**	2.73*	2.57*	2.63*
R Sup Parietal Lob (BA7)	28	-65	51	829	-	-	-	-	-	2.11*	2.06*	-	-	-	2.30*	2.60*	2.22*	2.34*	-
R Sup Parietal Lob (BA7)	24	-64	43	3185	2.19*	-	2.30*	-	2.21*	2.04*	2.11*	-	-	-	2.56*	2.99*	2.72*	2.99*	2.81*
L Sup Parietal Lob (BA7)	-30	-62	48	2718	2.15*	-	-	-	-	2.18*	2.24*	2.26*	2.05*	-	2.45*	2.75*	2.56*	2.55*	2.74*
R Insula (BA13)	36	17	5	1396	-	-	-	2.18*	-	2.09*	-	-	-	-	2.84*	2.72*	2.55*	2.67*	2.07*
L Insula (BA13)	-33	20	13	2619	-	-	-	-	-	2.08*	-	-	-	-	2.51*	3.04**	2.84*	2.64*	3.00**
L Precentral G (BA4)	-48	-9	43	1639	-	-	2.04*	2.22*	2.15*	2.24*	2.02*	2.17*	-	-	2.96*	3.02**	2.98*	3.03**	2.85*
L Precentral G (BA4)	-41	-14	53	807	-	-	-	-	-	2.27*	***1.90***	2.28*	-	-	2.45*	2.78*	2.12*	2.74*	2.45*
L Precentral G (BA6)	-28	-12	53	1064	-	-	-	-	-	***1.90***	2.15*	2.00*	-	-	***1.93***	2.79*	2.15*	2.05*	2.34*
R Precentral G (BA6)	26	-11	50	1320	-	-	-	-	-	***1.94***	2.04*	-	-	-	2.92*	3.14**	2.40*	2.93*	2.24*
R Precentral G (BA6)	42	-2	34	1491	-	-	-	-	-	2.13*	***1.93***	2.14*	2.18*	-	2.21*	2.76*	-	2.61*	2.63*
L Precentral G (BA6)	-45	-2	31	2906	2.08*	-	-	***1.99***	2.29*	2.19*	2.29*	2.22*	2.04*	2.05	2.98*	3.12**	2.84*	2.94*	3.08**
L Precentral G (BA6)	-54	2	37	1240	-	-	-	2.12*	2.04*	2.19*	-	2.25*	-	***1.99***	2.37*	2.40*	2.54*	2.15*	2.29*
L Precentral G (BA6)	-30	2	28	372	-	-	-	-	2.03*	-	-	-	-	-	2.20*	2.30*	-	-	***1.99***
R Inf Frontal G (BA9)	41	8	30	1744	-	-	-	-	-	2.25*	2.04*	2.35*	2.19*	-	2.49*	2.65*	2.27*	2.70*	2.62*
L Middle Frontal G (BA9)	-45	17	29	1709	2.09*	-	-	-	***1.99***	2.15*	2.28*	2.32*	2.29*	***1.93***	2.48*	2.98*	2.72*	3.01**	2.97*
L Middle Frontal G (BA46)	-42	24	22	232	-	-	-	-	2.05*	2.00*	2.19*	2.19*	2.28*	-	2.06*	2.66*	2.58*	2.25*	2.43*
R Middle Frontal G (BA9)	33	24	27	342	-	-	-	-	-	-	-	-	-	-	2.64*	2.55*	-	2.20*	-
L Middle Frontal G (BA10)	-43	41	10	147	-	-	-	-	2.00*	-	-	***1.92***	2.20*	***1.98***	-	2.09*	-	-	2.31*

							Holistic Low					***Holistic High***					***Component***		
Region	***x***	***y***	***z***	**#Vxls**	**HF**	**LF**	**Nov**	**Psd**	**Lett**	**HF**	**LF**	**Nov**	**Psd**	**Lett**	**HF**	**LF**	**Nov**	**Psd**	**Lett**
R Middle Frontal G (BA9)	35	45	27	672	-	-	-	-	-	2.35*	-	2.07*	-	-	2.37*	2.28*	2.51*	2.18*	-
L Anterior Cingulate (BA32)	-22	39	4	90	-	-	-	-	-	2.20*	-	-	-	-	2.48*	-	-	-	-
R Cingulate G (BA32)	8	14	37	862	-	-	-	-	-	***1.97***	***1.97***	***1.92***	***1.99***	-	2.64*	2.73*	2.41*	2.29*	2.45*

Skill Based Effects

In order to test the effects of Skill within the Holistic group, we employed an analysis of covariance model to determine the relationship between overall performance on the training component of the experiment and the cortical response to those trained items in the fMRI task. We computed average performance on the Word Identification task for each subject on the final two testing periods (Session4 Test3 and Session 5) for each subject. These scores were entered into the voxel-wise GLM model as covariates to be compared the planned comparison of trained Korean words (HF-K and LF-K) to the fixation control. Because these data could not meet the stringent FDR corrected alpha level of 0.05 yield a critical r-value of 0.98, we set the cluster threshold to 180mm (or 20voxels) and the p-value to 0.05. The resulting regions and correlation values are displayed in Table 6. From posterior to anterior these region include: a) ventral visual regions in right inferior occipital gyrus (BA17), left Cuneus (BA17), and bilateral fusiform gyrus (BA37); b) dorsal visual regions in right precuneus (BA7), superior parietal lobule (BA7); c) temporo-parietal regions in superior temporal gyrus (BA13) and inferior parietal lobule (BA40); d) anterior temporal regions in right fusiform gyrus (BA20) and left superior temporal gyrus/temporal pole (BA38); and frontal regions in left precentral gyrus (BA6), right middle frontal (BA6), left inferior frontal gyrus (BA9), right insular cortex (BA13), and left middle frontal gyrus. Several midbrain regions were also significantly correlated with performance including cingulate gyrus from the posterior portion bilaterally (BA31/23) to the medial anterior aspect (BA24). Other regions of interest include thalamus and caudate tail as well as the left Lentiform nucleus seen in previous analyses.

Table 6. Regions correlated with Word Identification Accuracy in the Holistic Training Group for Trained Novel Orthograpy words (HF-K + LF-K > Fixation)

Region	BA	x	y	z	r	Voxels
Positive Correlations						
Inferior Occipital Gyrus	17	16	-89	-7	0.73	567
Cuneus	17	-14	-74	9	0.71	440
Precuneus	7	4	-72	38	0.75	2620
Superior Parietal Lobule	7	-31	-67	50	0.71	271
Posterior Cingulate	31	-21	-63	17	0.71	224
Fusiform Gyrus	37	-40	-60	-24	0.72	372
Fusiform Gyrus	37	34	-58	-20	0.72	1365
Fusiform Gyrus	37	-42	-55	-13	0.72	300
Cingulate Gyrus	31	20	-50	23	0.72	955
Superior Temporal Gyrus	13	-35	-46	13	0.72	1087
Inferior Parietal Lobule	40	-44	-46	37	0.70	371
Caudate		31	-40	12	0.72	663
Fusiform Gyrus	20	-27	-39	-19		518
Posterior Cingulate	23	-8	-33	23	0.73	984
Thalamus	*	-3	-23	4	0.71	2529
Thalamus		9	-18	14	0.72	418
Thalamus		17	-13	7	0.70	212
Caudate		15	-9	28	0.71	460
Fusiform Gyrus	20	58	-9	-25	0.77	269
Precentral Gyrus	6	-41	-9	35	0.74	5128
Middle Frontal Gyrus	6	22	-9	47	0.71	489
Temporal Pole	38	-30	0	-35	0.72	186
Cingulate Gyrus	24	-3	5	38	0.75	4543
Lentiform Nucleus		-22	7	7	0.71	1326
Inferior Frontal Gyrus	9	25	9	27	0.72	613
Insula	13	37	15	5	0.72	1463
Middle Frontal Gyrus	9	-39	16	27	0.74	1084
Negative Correlations						
Medial Frontal Gyrus	8/9	-7	30	43	0.75	1102
Medial Frontal Gyrus	8	8	26	38	0.72	885
Inferior Frontal Gyrus	46	-46	42	2	0.76	2012

3.3 FMRI DISCUSSION

In terms of the neuroimaging results, our first goal in our analyses was to isolate the effects of native orthography conditions within the reading network. We wanted to isolate effects of frequency, lexicality, pronounceablility or legality that occur from native orthography stimulus conditions. As shown in Table 2, the results of our contrasts revealed an effect of word frequency in for English words in bilateral superior temporal gyrus (BA 21/22/39), the left insula (BA 13) and the right anterior cingulate (BA 32). Contrary to previous studies that have shown greater activation for low compared to high frequency words (Fiez et al., 1999; Assadollahi & Pulvermuller, 2003; Poldrack et al., 1999), the finding of our study reveal that high frequency words activated these regions more than low frequency words. Bilateral region of STG also showed effects of lexicality (BA 22/21/39) finding that words activated these areas to a larger extent than nonwords stimuli. Again, several studies have shown results to the contrary in which pronounceable nonwords activated this region to a larger extent (Paulesu et al., 2000; Pugh et al., 1996; Fiez et al., 1999); however, many studies have not shown this distinction (Tagamets et al., 2000; see Fiez et al., 1999 for discussion of this contrast). We failed to show any statistically significant differences between pronounceable/legal letterstrings compared to consonant strings.

We failed to support the posterior-anterior processing model in ventral inferior occipital-temporal cortex that was described in the introduction. Previous findings in support of this model (Cohen et al., 2000; 2002; Vorobyev et al., 2004) have shown that the posterior aspects of this network in the lateral occipital regions activate to all letterstring stimuli, whereas regions at the temporal junction/mid fusiform region activate to legal/pronounceable letterstrings, and more anterior regions of the inferior and middle temporal gyri activate to lexical stimuli (independent of modality). These contrary findings may have occurred as a result of the visual nature of the 1-

back memory task employed in this study. For instance, Tagamets et al. (2000) used a similar visually-based decision task as opposed to semantic or rhyme judgment tasks used in other studies of word reading (see for example Pugh et al., 1996; Paulesu et al., 1996) and failed to reveal differences between legal and illegal letterstrings particularly in superior and inferior temporal regions. Another reason for the failure to replicate these findings may have been the unusually long stimulus duration used in our study. Several findings have shown that letterstring differences particularly in the ventral visual processing stream can vary depending on duration of stimulus presentation (Price et al., 1996; Mechelli et al., 2003; Phillips et al., submitted). In particular, Phillips et al. (submitted) compared words and consonant strings at stimulus durations of 17, 35, 55, and 500ms followed by a visual mask. They found larger activation for words above nonwords at the three short durations (17, 35, and 55); however, at the 500ms duration a reversal of activation occurred with nonwords significantly more active than words in these same ventral visual regions including the putative word form region. We used a stimulus duration of 1500ms for both Korean and English words to enable identification of the novel orthography stimuli. Thus, more work is needed to understand how duration and task effects may produce the variations in findings for the comparisons of legality and lexicality of stimuli.

Comparison of Native and Novel Orthographies

In order to understand the impact of the novel Korean orthography compared to the native English orthography in our subjects, we performed a direct contrast of words in the two conditions. The results of this analysis, shown in Table 3, revealed larger overall activation for the novel compared to native orthography stimuli. That is, the novel Korean words activated most regions of the reading network bilaterally to a significantly greater extent than English words. These effects of novelty have been seen in studies involving training on new or variable stimuli (Poldrack et al., 1998; 2000; Chee et al., 2001). For example, Poldrack et al. (1998) trained subject on a mirror reading task and found that early in skill acquisition these participants activated a large network of bilateral regions particularly in inferior occipital-temporal regions as well in inferior frontal and prefrontal regions encompassing much of the reading network. They found that as training continued, activation of this network became less diffuse and more left lateralized particularly in these target regions of the reading network. They also found that as word recognition became less effortful, weaker activation was shown in the anterior cingulate and dorsal lateral prefrontal cortex (DLPFC) associated with executive functioning.

Of particular interest in our study is the activation of the left middle frontal gyrus for Korean compared to English stimuli. This region has been found to be particular active in Chinese word reading especially when compared with English word reading (Tan et al., 2005; Bolger et al., 2005; Nelson et al., submitted). According to Tan (et al., 2005) this region is hypothesized to function as a cross-modal integration mechanism that functions to select among generated lexical candidates to visually associated forms. That is, in Chinese, a given visual character is typically associated with a particular morpho-semantic concept but can cue several phonological candidate word forms. The middle frontal gyrus is presumed to integrate the visual information from the character with contextual semantic and phonological information to arrive at a particular spoken word form. Several studies of English word reading have also isolated this region for word reading compared to a resting baseline (Cohen et al., 2000; Jernigan et al., 1998; Price, 1996), for semantic priming and semantic decision making (Kotz et al., 2002; McDermott et al., 2003; Poldrack et al., 1999; Wagner et al., 2000), for pseudoword processing (Poldrack et al., 1999; Hagoort et al., 1998), for cross-modal priming (Carlesimo et al., 2004; Buckner et al., 2000) and for selective attention while reading (Cabeza et al., 2003; Shaywitz et al., 2001). Thus, the involvement of the middle frontal gyrus in this array of tasks and conditions together with its role in Chinese word reading suggests that cross modal integration may be involved. We also identify training and performance related differences in our study which we will discuss below. As for the comparison with Korean and English stimuli, given that this analysis included both component and holistically trained individuals and that we've highlighted a number of studies in English word recognition that do activate this region argues against the assumption that this region is involved in logographic word form processing.

The contrast of activation for English greater than Korean word stimuli revealed a large extent of left superior and middle temporal gyrus (BA 22/21) including much of the perisylvian region as well as the homologous region on the right hemisphere. This result suggests that activation of phonological information from the visual word stimuli was more facile for the English compared to Korean word stimuli. The specific role of the left STG has been largely debated particularly among models of word reading (see Temple, 2003) and verbal working memory (see Chein, 2004); however, this region has generally been implicated in auditory/phonological and receptive language processes (Paulesu et al., 1993; Pugh et al., 1996). In the 1-back fMRI task used in this study, some demands are placed on the episodic memory system in which storage of the corresponding phonological form would enable optimal performance. Given the relatively weak representations for the Korean word forms that the participants had, the ability to use this storage mechanism may have favored English stimuli over Korean stimuli, leading to the differences in activation. That is, because the task requires active storage of each stimuli to make a correct response, participants may have been more likely to activate the phonological form of the English words, but less capable of doing so in the case of

Korean in which case they may have used a more visual strategy—as evidenced by the larger bilateral visual processing discussed below.

Compared to the English stimuli, the Korean stimuli more strongly activated the bilateral ventral occipito-temporal region particularly the right fusiform, but more so for the right compared to the left mid-anterior fusiform. Bilateral activity in this region for word recognition has been largely associated with lower levels of recognition skill (Turkeltaub et al., 2004; Shaywitz et al., 2003; Poldrack et al; 2000; 2001; Simos et al., 2003); however, right hemisphere activation has also been exhibited for processing Chinese even in readers of both high and low skill (Tan et al., 2000; 2001; Bolger et al., 2005; Nelson et al., in press). This higher level of activation may be due to more domain general visual regions being recruited for weaker processing skill; however, in the skill based covariate analysis both right and left hemisphere fusiform regions were correlated positively with skill. Thus, the activation may have more to do with the visual-spatial processing required for the non-linear stroke patterns in the Korean orthography as has been suggested for Chinese character processing (Bolger et al., 2005; Nelson et al., in press). In contrast to the superior temporal region, there was an advantage for Korean processing in the superior and inferior parietal regions bilaterally suggesting greater demands on the orthographic-phonological decoding system. The role of the inferior and superior parietal cortices has been associated with the storage of phonological information (Pugh et al., 1996; Ravizza et al., 2003). However, this region has also been associated with the decoding of orthographic information (Pugh et al., 1996; Clark & Wagner, 2003) and has been shown to be more active for pseudowords compared to words (Clark & Wagner, 2003) and more active for low compared to high frequency items (Fiez et al., 1999). Greater activation was also shown for Korean stimuli in bilateral frontal regions including the insula and premotor cortex and importantly the left middle frontal gyrus. These results together suggest that the Korean stimuli required higher processing demands on systems involved in phonological decoding and output as suggested by the greater activation of the parietal and inferior frontal regions; whereas English stimuli more readily activated speech related regions of the STG.

Direct Comparisons of Training Conditions

One clear disappointment of this study was the lack of overall group differences in the individual contrasts between Component and Holistic and between each of these groups compared to the Control group. The lack of clear unique activations suggest that, in general, all three conditions are activating the reading network to a large extent as shown in the overall activation values across all groups. After reducing the stringent threshold values of the FDR correction, we did find a number of regions that differentiate between groups. Several regions were found to be more active for the Component compared to the Holistic group; however, no regions were more active for Holistic than Component training. Of particular importance is the left superior temporal gyrus. We postulated that holistic and component training both require the integration of visual and phonological lexical forms, but that the training of components requires the additional process of sublexical analysis and synthesis of letter-sound components. The left superior temporal gyrus has been implicated in the component processing of phonological forms (Paulesu et al., 1996; Temple et al., 2001; Booth et al., 2002; 2003). Thus, we conclude that this region is performing the phonological computations of letter-sound correspondences explicated in the component training.

In comparison to the Control group, the Component group activated the left insula and premotor regions that, as discussed earlier, are associated with phonological output processing (Poldrack et al., 1999; Fiez & Petersen, 1998; Pugh et al., 1996). Thus, the greater activation in this region may reflect the fact that the Component group used a more linguistic-based reading strategy to perform the 1-back task, whereas the Control group which received an abbreviated version of holistic training may have used a more visually based strategy. There was also more activation of the left substantia nigra and Thalamus both of which are associated with reward and learning processes. While there were no direct rewards or feedback provided in the task, the activation may reflect the internalized reward process from successfully decoding the word items for the Component group.

In comparison to the Control group, the Holistic group activated bilateral regions of the inferior parietal lobule. In addition to being associated with orthographic-phonological translation, the IPL has also been implicated for phonological processing of holistic word forms (Warrington & Shallice, 1979) and verbal working memory (Ravizza et al., 2003) suggesting that this result may be due to the attempt to generate and/or rehearse phonological word forms in the 1-back task. The Holistic group also showed greater activation for cingulate cortex than the Control group. This is consistent with the notion that the participants in the Holistic group may have employed more effortful processes to attempt to retrieve word form information from verbal working memory as opposed to the Control group with minimal training who may have used a purely visual process to perform the functional task.

ROI Analysis

We hypothesized that the Component group would internalize the letter-sound code and predicted that this would result in the Component group performing better on novel and pseudoword reading. These results were confirmed by the behavioral measures. We hypothesized that this effect of training would be reflected by cortical differences between the Component training and the Holistic training subsets. Differences between these groups are apparent for the conditions involving decoding knowledge (Novel words, Pseudowords, and Letters) particularly in the “dorsal” stream including bilateral regions of the superior and inferior parietal lobe (BA40 and BA7), left precentral and insular cortex (BA4/6 and BA13), and left anterior cingulate (BA32).

We presented two competing hypotheses that the holistic training would result in logographic reading or alternatively result in implicit derivation of the letter sound code. We hypothesized that given holistic training results in logographic processing, that differential cortical regions underlying letter-sound processing, such as the “dorsal” processing stream would be absent from logographic readers and that regions associated with logographic processing, such as the right ventral visual region and middle frontal regions would be present in logographic reading and absent in component reading. The findings of our behavioral study suggest that holistic reading produces both logographic reading (Low performers) and implicit component reading (High performers). The higher skilled readers performed more similarly to the component group on tasks of transfer, retention, and the effects of frequency. Thus, we hypothesized that differences between these high and low performers would reveal regions associated with alphabetic and logographic reading. Low skill readers activated only a limited set of regions overall for word reading, and these regions responded to high but not low frequency items including the left anterior VWFA (BA37), right inferior and superior parietal regions (BA40/7), and left precentral (BA6) and middle frontal regions (BA9). High skill readers activated much of the reading network for both low and high frequency items as well as novel and pseudoword items with the exception of the bilateral insula regions and which were only active for high frequency items. The component training condition activated all target regions for most conditions with the exception of the ventral aspect of the precentral and middle frontal gyri, which failed to activate for novel and pseudoword reading. Both the component and high skill holistic readers activated the anterior cingulate for high frequency words only.

With respect to the hierarchical model of the ventral inferior occipital-temporal regions, we found that the poor performing participants failed to activate more anterior regions of the right fusiform (BA20) and parahippocampal gyri (BA36) for words (however some activation was seen for pseudoword and letter stimuli) compared to high performing holistic participants who activated these regions particularly for HF word items. The component training group reliably activated the target ventral visual ROIs for all conditions (except for pseudowords in the parahippocampal region). Thus, our hypothesis that the right hemisphere homologues of the VWFA are more responsive for logographic reading is not supported. Rather, this region appears to respond to skill in learning novel orthography word stimuli, particularly for high frequency items. The left VWFA (BA37 at y=52) is active for HF word items for all three groups, and active for all conditions in the component training conditions; however, the high and low skill groups show differential patterns of activation with the latter group activating this region to pseudowords and letters and the former group to LF and novel words. Overall, the results of this analysis generally show that component training activates the entire network of reading related regions, whereas holistic training results in generally fewer, but critical, activated regions for the higher skilled group and limited activity localized in bilateral ventral visual regions in the lower skilled group.

Skill-based Correlational Analyses

Lastly, the skill based analysis conducted on the holistic group performance revealed a large portion of the reading network that was positively associated with reading skill. This activation consists of all of the regions discussed earlier: a) bilateral occipito-temporal regions including the VWFA and it's right hemisphere homologue, b) the left superior temporal region, c) the left inferior parietal region, d) left anterior temporal regions including the anterior fusiform/middle temporal gyri and the temporal pole, e) inferior frontal regions stretching into premotor cortex including the insula, and f) the middle frontal gyrus bilaterally.

Of particular interest is the activation of the left middle frontal gyrus, a region discussed earlier as having a greater presence in Chinese compared to English word processing (Tan et al., 2005). The fact that this region is more active for Korean stimuli than English stimuli in our results suggests that this region may in fact be recruited for effortful integration of multi-modal information. The question is whether this region is more active for holistic/logographic processing than for explicit or even implicit processing of letter-sound components. In the comparison between the Component and Holistic training groups, no differences are shown for this particular region; however, in the ANCOVA model correlation of skill within the holistic group, this middle frontal region has a strong positive correlation with skill. In the ROI analysis between training conditions, we find that the middle frontal region is strongly activated for the component group as well as the high performing holistic group suggesting that this region is performing an integration process and is responsive to skill. Therefore, this region is not associated with "logographic" reading per se, but appears to be correlated with skill in reading in the Korean orthography based on knowledge of the grapheme-phoneme structure of the writing system.

There were also negatively correlated regions in the left medial frontal region bordering the anterior cingulate and the left anterior lateral portion of the inferior frontal gyrus bordering on dorsal lateral prefrontal cortex. These negative correlations implicate regions associated with the central executive processes of response monitoring and selection (Cohen et al., 2000; Chein

& Schneider, 2003). Thus, skill acquisition in the (Holistic) training task involves increased activation in the network of regions associated with visual word recognition as well as decreases in activation of the central executive suggesting less effortful, more automatic processing.

4.0 GENERAL DISCUSSION

In order to understand the differences between alphabetic and logographic processing, we created a novel orthography training paradigm in which an alphabetic system (Korean) that is often confused with similar logographic systems (Chinese) is used to explore the behavioral and cortical differences between these two writing systems. We trained naïve native English speakers to learn to read (English) words in Korean Hangul script via a holistic (visual and phonological) word method or a component (phonics-based, letter-sound correspondences within word) method. We observed that compared to the holistically trained group, the component training resulted in faster learning, better retention of trained words, and better transfer to novel words. In addition, we found that the component training, compared to holistic training, was initially slower in terms of performance on a simple recognition task, after 4 sessions of training, this group was faster than the holistic group which did not significantly gain in recognition speed. In a manipulation of item frequency in training, we found that while the component training exhibited no sensitivity to frequency, the holistic training resulted in better accuracy and faster recognition time for high frequency compared to low frequency items.

Not all participants in the holistic training condition remained naïve to the alphabetic structure in the Korean Hangul script. As we predicted, at least half of the holistic training group acquired the letter-sound code. The performance of this group appeared similar to that of the Component training group in that they were faster learners, had better retention, and the ability to transfer knowledge to novel word items. Furthermore, this group of participants was nearly perfect at explicitly identifying the letter-sound relationships of the system. The group that failed to acquire this code exhibited extremely poor retention with decreasing trend lines were unable to transfer knowledge to novel items, and, after 4 sessions of training, could only explicitly identify less than half of the letter-sound relationships in the system. Thus, the difference between breaking the code or not reflects similar behaviors of alphabetic compared to logographic reading.

In order to fully understand how word recognition is achieved by the brain, it is critical to understand the way in which the network of cortical regions responds before and after learning occurs. Pugh et al. (2001) suggests that in the development of reading ability the dorsal (left posterior temporo-parietal) circuit predominates early learning reflecting effortful phonological decoding of orthographic stimuli, and that a word form region (VWFA) develops later in skill (possibly through feedback) as word recognition becomes increasingly automatic. This neurobiological account is similar to cognitive development accounts of reading that pose that decoding knowledge is a bootstrapping mechanism to establishing orthographic word forms (Share, 1995). The impact of training studies in fMRI such as this one is that they enable us to observe these changes in cortex associated with orthographic learning and skill development.

According to our cognitive framework of reading development (Share, 1995; Perfetti, 1992), mapping of visual letters to their corresponding phonological features in the spoken language, the alphabetic principle, is the initial stage of word recognition. In our neurobiological model, the lateral ventral occipital regions such as the bilateral posterior fusiform (V4) are found to be activated by all letterstrings invariant of case, font, and position (McCandliss et al., 2000; Gauthier et al., 2000). This region is suited for abstract letter processing, in that it does not exhibit sensitivity to legal compared to illegal orthographic forms. This region is believed to project to left angular/supramarginal gyrus in the inferior parietal-occipital region. Among other functions, this region of cortex has been argued to perform letter-sound computations (Booth et al., 2003; 2004; Pugh et al., 2001; Paulesu et al., 1993; Crosson et al., 2004). This region also has functional relationships (Horowitz et al., 1997; Pugh et al., 2000; Rumsey et al., 1997) as well as structural relationships (Klingberg et al., 2001) with posterior inferior frontal gyrus and inferior temporal regions correlating with reading skill. This pathway is argued to be the early developing dorsal route for decoding orthography to phonology (Pugh et al., 2001). The findings in our study suggest that the inferior parietal cortex is strongly related to skilled performance and acquisition of the letter-sound code for both the component trained group and the high performing holistic group who derived this knowledge implicitly. This region was also more active for the component and holistic group compared to the low trained control group.

The second component of our cognitive framework is the development of word form representations of the words encountered and successfully decoded. According to this framework, the specificity of these representations depends on the number of encounters a reader has with the word, thus this component can be slow developing considering the large number of lexical items in a given language and the amount of experience a reader has with them (Perfetti, 1992). In the same way, the cortical word form network in the left inferior temporal region develops more slowly over time with word recognition (Pugh et al., 2000; 2001; Shaywitz et al., 2002; McCandliss et al., 2003). This VWFA has been shown to be sensitive to abstract, prelexical legal word forms (Cohen et al., 2000; 2002; Dehaene et al., 2001; Farah et al., 2002; Vorobyev et al., 2004).

The expertise hypothesis (McCandliss et al., 2003; Gauthier, 2000) suggests that this sensitivity difference may be driven by experience with a particular class of stimuli. More specifically, expertise with a class of stimuli results in increased sensitivity to form ***within*** a class of stimuli, and thus is posited to drive more abstract form-based processing in anterior regions of IT (Gauthier, 2000). In fMRI investigations of visual expertise, Gauthier et al (1999, 2001) found that an area in the right fusiform gyrus that elicits particular sensitivity to faces, the fusiform face area (refered to as the FFA; Kanwisher et al., 1997), became increasingly sensitive to a novel class of stimuli, "greebles", which share similar spatial frequencies and visual contours to faces, after training subjects to identify individual greeble forms and classifications of forms (i.e. gender and family). Longitudinal studies of learning to read using fMRI (Shaywitz et al., 2002; 2003) have found that activation within the region of the VWFA correlates highly with reading skill emerging around 9-10 years in age. Similarly, remediation studies in fMRI of poor and impaired readers (Temple et al., 2002; Shaywitz et al., 2004; McCandliss et al., unpublished findings) finds increases in activation of the VWFA following intensive training. These patterns persist 1-3 years post-training (Shaywitz et al., 2004).

In terms of the findings of this study, the left VWFA does correlate with reading skill in the holistic training condition; however, no differences were exhibited in this region for component compared to the low trained control group suggesting it may not be progressing with reading skill in our study. Furthermore, the Arabic control stimuli in this study showed equally strong activation in this region compared to word forms even in the native orthography. In a recent study by Xue et al. (in press), they trained native Chinese speakers to read Korean as a logographic writing system. They found that the highest activations in the VWFA for Korean stimuli occurred before training suggesting that this region responds to novelty and shows decreases with experience with orthographic features. Similar results obtained in a study by Bolger & Schneider (2002) also found that the putative VWFA responded to Greek letter strings as strongly as to English words and pseudowords; however, this region only exhibited neural adaptation to repeated English stimuli but not to Greek letter strings. Thus, these findings suggest that the VWFA and similar regions of cortex may elicit fine tuning with experience, primarily by decreasing noise as opposed to increasing signal (Gotts, 2001; Macotta & Buckner, 2004; Carlesimo et al., 2004). Tagamets et al (2000) also failed to find word form preferences in the VWFA, but found that the ventral occipital-temporal region exhibited more bilaterally activation for linguistically illegal structures (consonant strings and false fonts) and more defined activation in anterior left lateralized regions of inferior temporal cortex particularly the VWFA for legal forms (words and pseudowords).

One argument is that right hemisphere ventral visual regions function to support domain-general visual recognition processes and thus are recruited for processing less familiar word forms. Several findings have shown activation in the right fusiform region to decrease as a function of reading skill (Turkeltaub et al., 2003; Shaywitz et al., 2002; 2003; Poldrack et al., 1998; 2000). However, studies of reading in Chinese have shown this region to be consistently active for skilled reading (Tan et al., 2001; 2002; Bolger et al., 2005) and to activate for native English speakers learning to read Chinese (Liu et al., in press; Nelson et al., submitted). Furthermore, activation centered in the right medial temporal regions have been shown to predict successful encoding of words (Ranganath et al 2004; Wise et al.,2000). The findings in our fMRI study reveal strong skill related effects in the right fusiform and parahippocampal regions for the component group, the high performing holistic group, and the low performing holistic group on high frequency words. Thus, as suggested by Gauthier et al (2001) this right hemisphere region may play a role in discriminating among a series of similar visual forms, possibly by enabling episodic traces to remain active. That is, our Korean learning paradigm, like Chinese reading, contains a limited set of graphic features that compose a larger set of word items. In order to maintain the episodic traces of these visual forms long enough to enable accurate word form selection these right hemisphere regions remain active until lexical selection can occur.

Both the early developing dorsal route and the later emerging ventral route project to the left inferior frontal/premotor region that is implicated in articulatory output and semantic integration. The role of posterior inferior frontal cortex has been associated with verbal working memory (Chein et al., 2002; Paulesu et al., 1993), with phonological decoding of orthographic forms (Pugh et al., 1996; Fiez & Petersen, 1998; Poldrack et al., 1999), and with phonological judgments (Price et al., 1997; Zatorre et al., 1996). In our study, this region was found to be significantly more active for the component compared to the control group, correlated with reading skill in the holistic group, and active for the component and high skill, but not low skill holistic group. Thus, this region appears to reflect learning of the letter-sound code in our experimental paradigm.

The other region in our task that appears to correlate with skilled reading performance is the left middle frontal gyrus. As we discussed, this region has been shown to be more active for native Chinese compared to native English speakers reading in their respective languages (Tan et al., 2005; Bolger et al., 2005). In Chinese this region appears to correlate with reading skill (Tan et al., 2001) and to show deficits in Chinese dyslexics (Siok et al., 2003). This region is suggested to serve cross-modal lexical selection (Tan et al., 2005). However, it has been shown to be activated for English pseudowords and semantic judgments suggesting that it may be integrative at the sublexical level as well. In our study, this region was more active for Korean than for English stimuli. Activation was more widespread in this region for the component and high skilled holistic compared to low skill holistic learners, which was replicated in the correlational analysis within the holistic group. Thus, according to our findings, the middle frontal region is also a skill based region for novel orthography learning, particularly for readers who have sufficiently acquired the letter-sound correspondences of the writing system.

In sum, our study suggests that acquisition of decoding knowledge is critical to learning to read in an alphabetic writing system and is most efficiently acquired through explicit training of the components. Implicit acquisition of this decoding knowledge fundamentally relies on individual differences in the ability to attend to the sublexical structures of the phonological system and readily map them onto the corresponding orthographic units. The ability to decode the component structures of the writing system leads to the ability to generalize knowledge to novel words and to subsequently bootstrap into word form representations leading to greater retention and fluency of word recognition. Several cortical structure appear to subserve the process of acquiring this sublexical knowledge and lead to privileged word form identification. These structures are consistent with the 'dorsal route' of the left inferior parietal and superior temporal gyrus along with the posterior inferior frontal/premotor region. Also implicated in this skilled reading network are the left middle frontal gyrus and the right inferior and medial temporal regions. The former region is presumed to play a role in integrating information across modalities while the latter region is presumed to play a role in the episodic encoding of the visual word form information to enable accurate lexical selection.

4.1 CONCLUSION

In order to understand the differences between alphabetic and logographic processing, we created a novel orthography training paradigm in which an alphabetic system (Korean) that is often confused with similar logographic systems (Chinese) is used to explore the behavioral and cortical differences between these two writing systems. We trained naïve native English speakers to learn to read (English) words in Korean Hangul script via a holistic (visual and phonological) word method or a component (phonics-based, letter-sound correspondences within word) method. We observed that compared to the holistically trained group, the component training resulted in faster learning, better retention of trained words, and better transfer to novel words. In addition, we found that the component training, compared to holistic training, was initially slower in terms of performance on a simple recognition task, after 4 sessions of training, this group was faster than the holistic group which did not significantly gain in recognition speed. In a manipulation of item frequency in training, we found that while the component training exhibited no sensitivity to frequency, the holistic training resulted in better accuracy and faster recognition time for high frequency compared to low frequency items.

Not all participants in the holistic training condition remained naïve to the alphabetic structure in the Korean Hangul script. As we predicted, at least half of the holistic training group acquired the letter-sound code. The performance of this group appeared similar to that of the Component training group in that they were faster learners, had better retention, and the ability to transfer knowledge to novel word items. Furthermore, this group of participants was nearly perfect at explicitly identifying the letter-sound relationships of the system. The group that failed to acquire this code exhibited extremely poor retention with decreasing trend lines were unable to transfer knowledge to novel items, and, after 4 sessions of training, could only explicitly identify less than half of the letter-sound relationships in the system. Thus, the difference between breaking the code or not reflects similar behaviors of alphabetic compared to logographic reading.

In order to fully understand how word recognition is achieved by the brain, it is critical to understand the way in which the network of cortical regions responds before and after learning occurs. Pugh et al. (2001) suggests that in the development of reading ability the dorsal (left posterior temporo-parietal) circuit predominates early learning reflecting effortful phonological decoding of orthographic stimuli, and that a word form region (VWFA) develops later in skill (possibly through feedback) as word recognition becomes increasingly automatic. This neurobiological account is similar to cognitive development accounts of reading that pose that decoding knowledge is a bootstrapping mechanism to establishing orthographic word forms (Share, 1995). The impact of training studies in fMRI such as this one is that they enable us to observe these changes in cortex associated with orthographic learning and skill development.

According to our cognitive framework of reading development (Share, 1995; Perfetti, 1992), mapping of visual letters to their corresponding phonological features in the spoken language, the alphabetic principle, is the initial stage of word recognition. In our neurobiological model, the lateral ventral occipital regions such as the bilateral posterior fusiform (V4) are found to be activated by all letterstrings invariant of case, font, and position (McCandliss et al., 2000; Gauthier et al., 2000). This region is suited for abstract letter processing, in that it does not exhibit sensitivity to legal compared to illegal orthographic forms. This region is believed to project to left angular/supramarginal gyrus in the inferior parietal-occipital region. Among other functions, this region of cortex has been argued to perform letter-sound computations (Booth et al., 2003; 2004; Pugh et al., 2001; Paulesu et al., 1993; Crosson et al., 2004). This region also has functional relationships (Horowitz et al., 1997; Pugh et al., 2000; Rumsey et al., 1997) as well as structural relationships (Klingberg et al., 2001) with posterior inferior frontal gyrus and inferior temporal regions correlating with reading skill. This pathway is argued to be the early developing dorsal route for decoding orthography to phonology (Pugh et al., 2001). The findings in our study suggest that the inferior parietal cortex is strongly related to skilled performance and acquisition of the letter-sound code for both the component trained group and the high performing holistic group who derived this knowledge implicitly. This region was also more active for the component and holistic group compared to the low trained control group.

The second component of our cognitive framework is the development of word form representations of the words encountered and successfully decoded. According to this framework, the specificity of these representations depends on the number of encounters a reader has with the word, thus this component can be slow developing considering the large number of lexical items in a given language and the amount of experience a reader has with them (Perfetti, 1992). In the same way, the cortical word form network in the left inferior temporal region develops more slowly over time with word recognition (Pugh et al., 2000; 2001; Shaywitz et al., 2002; McCandliss et al., 2003). This VWFA has been shown to be sensitive to abstract, prelexical legal word forms (Cohen et al., 2000; 2002; Dehaene et al., 2001; Farah et al., 2002; Vorobyev et al., 2004).

The expertise hypothesis (McCandliss et al., 2003; Gauthier, 2000) suggests that this sensitivity difference may be driven by experience with a particular class of stimuli. More specifically, expertise with a class of stimuli results in increased sensitivity to form ***within*** a class of stimuli, and thus is posited to drive more abstract form-based processing in anterior regions of IT (Gauthier, 2000). In fMRI investigations of visual expertise, Gauthier et al (1999, 2001) found that an area in the right fusiform gyrus that elicits particular sensitivity to faces, the fusiform face area (refered to as the FFA; Kanwisher et al., 1997), became increasingly sensitive to a novel class of stimuli, "greebles", which share similar spatial frequencies and visual contours to faces, after training subjects to identify individual greeble forms and classifications of forms (i.e. gender and family). Longitudinal studies of learning to read using fMRI (Shaywitz et al., 2002; 2003) have found that activation within the region of the VWFA correlates highly with reading skill emerging around 9-10 years in age. Similarly, remediation studies in fMRI of poor and impaired readers (Temple et al., 2002; Shaywitz et al., 2004; McCandliss et al., unpublished findings) finds increases in activation of the VWFA following intensive training. These patterns persist 1-3 years post-training (Shaywitz et al., 2004).

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