Cognitive Processes and Neural Correlates of Reading in Languages with Graded Levels of Orthographic Transparency:
Spanish, English and Hebrew

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Abstract

This thesis examined the cognitive processes and neural correlates involved in reading Spanish (a transparent orthography), English (an intermediate orthography) and Hebrew (an opaque orthography) by bilinguals and trilinguals.

The main objectives of the five experiments were to: (i) extend previous findings which demonstrated that orthographic transparency influences the degree of reliance on lexical and sublexical processing, and (ii) assess the effects of orthographic transparency and language proficiency on strategies employed for reading in a second and third language.

Word/non-word naming tasks undertaken by Spanish-English bilinguals, Hebrew-English bilinguals and English monolinguals, where frequency, length and lexicality were manipulated, showed a predominant reliance on sublexical processing in Spanish, lexical processing in Hebrew, and a balanced interplay in English. Effects of language proficiency were also observed as slower naming and lower accuracy in English as a second language. Concurrently, while showing an efficient adaptation of reading strategy to the level of orthographic transparency of English, Hebrew bilinguals appeared to show stronger reliance on sublexical processing than Spanish bilinguals, suggesting a compensatory mechanism.

fMRI experiments showed that reading in all languages was associated with a common network of predominantly left-lateralised cerebral regions. Reading in each language was associated with some preferential activation within regions implicated in lexical and sublexical processing, in keeping with their graded levels of orthographic transparency. Effects of language proficiency were demonstrated as increased activation within medial frontal regions implicated in attentional processes as well as right-lateralised homologous language-processing regions. Furthermore, the patterns of activation seen in Hebrew readers in English strengthened the notion of a compensatory mechanism.

Finally, a trilingual experiment replicated findings observed in bilinguals, revealed the acute complexity of reading in Hebrew as an additional language and further strengthened the concept of a compensatory mechanism in English and Spanish.

The present findings further contribute to current knowledge on teaching methods, diagnostic tools and therapeutic strategies for developmental and acquired reading disorders.

“Neither can embellishments of language be found without arrangement and expression of thoughts, nor can thoughts be made to shine without the light of language”.

Marcus Tullius Cicero (106 – 43 BC)

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It is often said that conducting research for a PhD and particularly writing a PhD thesis is a laborious, frustrating and lonely experience. While I must admit that it has been an arduous undertaking, for me this task has also been fascinating, thought-provoking and inspiring.

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Though I will look back on this time with great relief at the accomplishment of such a tremendous task, I shall also miss it greatly.

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Chapter 1

Introduction

The “light of language” is one of the hallmarks of humanity. It enables us to formulate thoughts, exchange ideas, alert each other to danger, make requests, express feelings, expand our knowledge and essentially function within a society. Equally, the “art of reading” (Quiller-Couch, 1920) has become an essential tool for survival. It enables us to enjoy literature, read the newspaper, decipher train timetables, identify products in the shop, study history, science and art, correspond through post, email, Facebook, and examine PhD theses.

The remarkable ease with which infants learn to understand verbal language and transform mental representations of the surrounding environment into a sequence of sounds suggests that throughout the course of evolution, the human brain has developed an expertise for its processing. On the other hand, learning to visually decode and comprehend written language in the process of reading is an aspect of human communication that has emerged relatively late in human history, and requires effort and purposeful integrated learning. Since writing-systems emerged in order to communicate spoken language, and reading and writing are achieved through the integration of visual and verbal information, it is not surprising that these abilities should be mediated largely by the same cerebral regions involved in spoken language processing (Pinker, 1994; Maynard Smith & Szathmary, 1995; Price, 2000).

Much insight into the functional organization of language representation in the brain has been provided through reported cases of acquired language impairments following brain damage. Acquired speech disorders such as aphasia (e.g. Broca, 1861; Wernicke, 1874; Lichtheim 1885), reading impairments such as alexia (e.g. Dejerine, 1892) and dyslexia (e.g. Marshall & Newcombe, 1973), and writing disorders, such as dysgraphia (e.g. Hatfield & Patterson, 1983; Hatfield, 1985), have often been associated with damage to specific left-lateralised regions, leading to their labelling as putative language processing areas.

Across the world, languages consist of a plethora of phonetic characteristics, grammatical structures, scripts, writing-systems and orthographic properties. The ability of humans to spread across the globe and adapt to new environments has given rise to the phenomenon of multilingualism, characterised by the ability to function in two languages or more, whether restricted to verbal communication, or expanded to literacy (Valdes, 2001). Communicating verbally and literally in different languages provides a means of unifying the diverse cultures of the world, and facilitates travel and exchange of information internationally and interculturally. This remarkable ability exemplifies the versatility of the human brain, capable of synthesizing and processing information in one language and deciphering codes in another without apparent interference. However, while the healthy human brain is capable of processing two or more languages, intriguing phenomena have been observed in bilingual and multilingual individuals with cortical lesions showing selectively manifested impairments in the different languages, such as loss of one language but not the other, differential patterns of recovery (Paradis, 1977), pathological mixing and switching between languages (Potzl, 1983; Kauders, 1983), inability to translate from one language to another, and translation without comprehension (Fabbro & Gran, 1997).

These observations have raised several questions regarding the functional organisation of multilingual brains, such as whether multiple languages are represented in separate or overlapping cortical regions, or whether differentially manifested impairments may be attributed to the location of the lesion. In addition, other factors, such as patients' proficiency in each of the languages, the age of their acquisition, the level of exposure to each language, or the linguistic properties of the languages may influence the occurrence of such impairments.

Since the early 20th century, the answers to these questions have been sought by inferring the function of cortical structures associated with language processing, through cases of language impairments associated with brain damage, relying primarily on neuropsychological and behavioural methods (e.g. Hinshelwood, 1902; Durgunoglu & Roediger, 1987; Snodgrass, 1992; Roberts & Le Dorze, 1998). More recently, the development of functional neuroimaging techniques, such as electroencephalography (EEG), magnetoencephalography (MEG), positron emission tomography (PET) and functional magnetic resonance imaging (fMRI), has enabled the visualization of specific foci related to language representation by detecting local changes in correlates of neuronal activation occurring *in vivo* (e.g. Pugh, Shaywitz Shaywitz, Constable, Skudlarski, Fulbright, Bronen, Shankweiler, Katz, Fletcher & Gore, 1996; Fiez; Balota; Raichle & Petersen, 1999; Wydell, Vuorinen, Helenius, & Samelin, 2003; McDermott, Petersen, Watson & Ojemann, 2003; Joubert, Beauregard, Walter et al, 2004; Booth, Lu, Burman, Chou, Jin, Peng, Zhang, Ding, Deng & Liu, 2006; Bick, Goleman & Frost, 2008). While a great body of knowledge has emerged from these studies regarding monolingual language processing, much remains unresolved in the domain of multilingualism. For example, while some investigators have shown different areas of activation during exposure to a second language, relative to a first language (Klein, Zatorre, Milner, Meyer & Evans, 1994; D’esposito & Alexander, 1995; Kim, Relkin, Lee & Hirsch, 1997), others have found largely overlapping regions associated with multiple-language representation (Yetkin, Haughton & Cox, 1996; Chee, Tan & Thiel, 1999; Pu, Liu, Spinks et al, 2001; Hernandez, Martinez & Kohnert, 2000; Hernandez, Dapretto, Mazziotta & Bookheimer, 2001; Vingerhoets, Van Borsel, Tesink et al, 2003; Briellmann, Saling, Connell, Waites, Abbott & Jackson, 2004; Meschyan & Hernandez, 2005; Halsband, 2006).

In 1989, François Grosjean published a review entitled “Neurolinguists beware! – The bilingual is not two monolinguals in one person”. The author noted that the unique and specific attributes of each of the languages, the context in which they are used and the age of their acquisition render each bilingual individual a “unique and specific speaker-hearer” (p.6). This contention, of course extends to literacy, whereby each biliteral individual must also be a unique and specific writer-reader.

Most written languages are structured in a universal hierarchical pattern. Texts are composed of sentences, arranged according to grammatical rules, sentences are assembled from words, arranged according to syntactic rules, and words consist of sounds (‘phonemes’), arranged according to phonetic rules. In logographic writing-systems such as Chinese and Japanese Kanji, phonemes do not form part of written text since these languages use symbols to directly convey meaning. In syllabic writing-systems such as Japanese Kana phonemes form part of a relatively large linguistic unit – the syllable. In alphabetic writing-systems phonemes are encoded by letters or letter-clusters (‘graphemes’), which are arranged according to orthographic rules, though the level of correspondence between the graphemic units of the writing-system (print) and their phonetic representations (sound) may vary greatly between different languages.

The level of correspondence between graphemes and phonemes is often quantified in terms of ‘orthographic depth’ (Frost, Katz & Bentin, 1987) or more recently, ‘orthographic transparency’ (c.f. Wydell & Butterworth, 1999). For example, in languages such as Spanish, Italian and Finnish, vowel sounds are usually straightforward and consistent: the letter ‘*a*’ is pronounced as in ‘*car*’, ‘*e*’ is pronounced as in ‘*den*’, ‘*i*’ is pronounced as in ‘*see*’, ‘*o*’ is pronounced as in ‘*cot*’ and ‘*u*’ is pronounced as in ‘*boot*’. These languages can therefore be regarded as highly phonetic, ‘shallow’ or ‘transparent’. By contrast, in languages such as English and French, several different phonemes may be represented by the same graphemes, rendering their orthographies ‘deeper’ or less transparent. For example in

French, the phoneme /o:/ can be represented simply with the letter ‘*o*’ as in ‘*dos*’ (back), or with the letter cluster ‘*eau*’ as in ‘*gâteau*’ (cake), and in English the phoneme /i:/ can be represented in various forms, such as ‘*ea*’ in ‘eat’, ‘*ee*’ in ‘feet’, and ‘*ie*’ in ‘*achieve*’. Among the least transparent alphabetic orthographies are Arabic and Hebrew. In these languages vowels are depicted by diacritical marks, which consist of points and dashes placed under or above consonants. However, as will be described in detail in the next chapter, these marks are omitted in everyday texts. Written Arabic and Hebrew therefore consist almost entirely of consonants and phonemic information is essentially missing.

Several studies using behavioural methods have suggested that reading in languages with different levels of orthographic transparency may involve distinct reading strategies (e.g. Frost, Katz & Bentin, 1987; Baluch & Besner, 1991; Tabossi & Laghi, 1992; Frost, 1994; 1995; Ziegler, Perry, Jacobs & Braun, 2001; de Groot, Borgwaldt, Bos & Eijnden, 2002; Abu Rabia & Siegel, 2003; Benuck & Peverly, 2004; Ellis, Natsume, Stavropoulou, et al, 2004). For example, in Spanish, as a transparent orthography, any word can be pronounced correctly simply by assigning to each written consonant the sound of the vowel that follows, a process often referred to as ‘phonological recoding’ (Frederiksen & Kroll, 1976) or ‘assembly’ (McCann & Besner, 1987). However in English, while this strategy might lead to correct pronunciation of some words, e.g. *desk*, *cat*, *shrub*, other words may require lexical knowledge, since the actual pronunciation is not in keeping with the phonemic spelling, e.g. *gauge*, *yacht* and *cough*. Moreover in Hebrew, the absence of written vowels renders phonological assembly utterly inefficient, and the correct pronunciation of words must therefore be inferred through lexical knowledge or reliance on the context in which the words are placed (c.f. Katz & Frost, 1992).

Different levels of orthographic transparency have also been suggested to influence the efficiency and speed at which fluent reading is achieved by young children (e.g. Caravolas & Bruck, 1993; Ellis & Hooper, 2001; Spencer & Hanley, 2003; Ziegler & Goswami, 2005; 2006) as well as give rise to differentially manifested symptoms of acquired and developmental reading disorders (e.g. Wydell & Butterworth, 1999; Ratnavalli, Geetha, Murthy et al, 2000; Beland & Mimouni, 2001; Karanth, 2002; Obler & Gjerlow, 2002).

Moreover, suggestions that distinct cortical regions may mediate the different types of processing associated with reading in languages with varying levels of orthographic transparency have been put forward and examined using neuroimaging techniques (e.g. Illes, Francis, Desmond et al, 1999; Paulesu, McCrory, Fazio et al, 2000; Moreno & Kutas, 2005; Meschyan & Hernandez, 2005; Simon, Bernadr, Lalonde & Rebaï, 2006).

To date, most behavioural and neuroimaging studies have relied upon within- and between-language comparisons with monolinguals (e.g. Frost et al, 1987; Frost 1994; 1995; Baluch & Besner, 1991; Paulesu et al, 2000; Ziegler et al, 2001) and bilinguals (e.g. Illes et al, 1999; Wydell & Butterworth, 1999; de Groot et al, 2002; Meschyan & Hernandez, 2005;

Simon et al, 2006), but only few have addressed the issue of multilingualism (e.g. Yetkin et al, 1996; Wattendorf, Westermann, Zappatore et al, 2001; Vingerhoets et al, 2003; Abu-Rabia & Siegel, 2003; Briellmann et al, 2004; Van Hell & Dijkstra, 2002; Lemhofer et al, 2004). Furthermore, while reading in Hebrew has been extensively studied using behavioural measures (e.g. Frost et al, 1987; Frost 1994; 1995; Gollan, Forster & Frost, 1997; Benuck & Peverly, 2004), no reported neuroimaging study has made use of the uniqueness and versatility of this language for a cross-language comparative study of reading in the brain.

The present study employs behavioural methods in conjunction with fMRI to address the question of how reading in different languages is processed and mediated in the brains of healthy multilinguals. Of particular interest in the present investigation are the processes involved in reading three languages which carry graded levels of orthographic transparency, and can therefore be viewed as placed along a ‘continuum’, with Spanish as a transparent orthography, English as an intermediate orthography and Hebrew as an opaque orthography.

The next chapter reviews the literature comprising the cornerstone of the present study. This is followed by 5 experiments conducted with bilinguals and trilinguals of Spanish, English and Hebrew, using behavioural measures and fMRI, aimed at answering three key questions:

1. What are the effects of the graded levels of orthographic transparency of Spanish, English and Hebrew writing-systems on reading strategies employed by native readers?

2. How are the different types of strategies employed for reading in these three languages mapped at the cortical level?

3. How do the orthographic properties of the native language affect the reading strategies employed in a second and third language?

Finally, the study addresses how the findings from the combined behavioural and neuroimaging methodology of the present study can account for existing theories for reading in languages with different orthographic properties, and whether the present findings could contribute to the development of efficient teaching strategies and remedial interventions for developmental and acquired reading disorders.

Chapter 2

Literature Review

2.1 Introduction

"…you and I belong to a species with a remarkable ability: we can shape events in each other's brains with exquisite precision. I am not referring to telepathy or mind control or the other obsessions of fringe science; even in the depictions of believers these are blunt instruments compared to an ability that is uncontroversially present in every one of us. That ability is language. Simply by making noises with our mouths, we can reliably cause precise new combinations of ideas that arise in each other's minds. The ability comes so naturally that we are apt to forget what a miracle it is".
(Pinker, 1994, p.15; The Language Instinct)

How the remarkable phenomenon of language is mastered so naturally that it has been termed an 'instinct' (Pinker, 1994) and how the need for expanding forms of communication have led to the development of writing-systems has been, and continues to be thoroughly studied throughout the past 150 years.

In contrast to verbal language, reading and writing cannot be viewed as instinctive, since their achievement and mastery comes about through effortful training rather than natural acquisition through the surrounding environment. Even so, in this day and age, literacy is essential for normal functioning as much as instinctive traits such as eating, drinking, sleeping and indeed speaking. Moreover, in this ever-changing and expanding world, speaking and understanding more than one language poses a tremendous advantage, enabling the exchange of information between countries and bringing different cultures closer. At the same time, growing up with two or more languages may sometimes lead to disadvantages, such as attributing delay or difficulties in speech and reading acquisition to interference of an additional language, thereby possibly ignoring an underlying deficit or disability, which may be remediated if identified early (Geva, 2000; Everatt, Smythe, Ocampo & Gyarmathy, 2004). These points highlight the importance of understanding how this non-instinctive yet so wide-spread trait of human communication is achieved.

This chapter reviews the key literature that forms the background to the present investigation. The studies reported in this literature review are presented in a combined order of chronology and relevance to the questions listed in Chapter 1. First, section 2.2 presents an overview of early observations of language disorders associated with brain damage leading to the identification of cerebral structures involved in verbal and written language processing, while section 2.3 provides an outline of models and theories regarding the types of processes thought to be specifically involved in visual word recognition, supported by a brief review of behavioural and neuroimaging studies. Then, the phenomenon of multilingualism is addressed in section 2.4 and finally, section 2.5 presents a detailed review of behavioural and neuroimaging studies that have focussed on understanding the processes associated with reading in different languages, particularly those with varying levels of orthographic transparency. This is followed by a summary of the orthographic properties of the three languages chosen for the present study.

2.2 Language processing in the brain

Humans are the only mammals who cannot breathe and drink simultaneously. This is due to the low position of the larynx within the human throat, creating a vocal tract with a horizontal oral tube and a vertical pharyngeal one (Lieberman, McCarthy, Hiiemae & Palmer, 2001). This dual-tube vocal tract allows the production of vowel sounds, which would not be attainable if the human larynx had been located in the same high position as in other mammals. Therefore the 'descent of the larynx', giving rise to the human 'speech apparatus' has been a major transition in human evolution, without which the evolution of spoken language would have been impossible (Maynard Smith & Szathmary, 1995). Effective language use requires the integration of sensory input, motor output and executive functions such as phonological, orthographic and semantic memory and attention (Price 2000; Fernandez-Duque & Posner, 2001). Given that the human body contains a unique organ for speech, it is not surprising that the human brain should contain specialised regions for its mediation. Current knowledge about those regions has come from a myriad of studies using diverse types of methods, from lesion studies to structural and functional neuroimaging.

2.2.1 Inferring cerebral function through observed dysfunction

While most high cognitive functions cannot be said to be localised in particular cerebral regions, language processing has been repeatedly associated with a number of regions, predominantly within the left cerebral hemisphere, as first pointed out by French physician Paul Broca in 1861. Broca noted that damage to the left inferior frontal gyrus (IFG), adjacent to the face area of the motor cortex, led to deficits in speech generation and fluency, coupled by intact comprehension.

Similarly, in 1874, German neurologist and psychiatrist Carl Wernicke identified another type of disorder, characterised by impaired comprehension and incoherent, yet fluent speech. This type of impairment, sometimes referred to as fluent, or Wernicke’s aphasia, was attributed to lesions in the left superior temporal gyrus (STG), located between the primary auditory cortex and the angular gyrus, within the association cortex. The dissociability between these two types of impairments has led to the notion that while the IFG may be involved in the mediation of language production, the STG may play a predominant role in language comprehension.

In 1885, German physician Ludwig Lichtheim reported the case of an aphasic patient who exhibited inability to repeat sentences and a tendency to generate semantically anomalous speech, with otherwise unimpaired comprehension and utterance. Following a post mortem examination, it was discovered that the patient had suffered damage to a bundle of white matter fibres referred to as the arcuate fasciculus, which connects the IFG and STG. The type of aphasia associated with lesions to this tract is now referred to as ‘conduction aphasia’ (Gazzaniga, Ivry & Mangun, 1998). Towards the end of the 19th century the French neurologist Joseph Jules Dejerine (1892), identified 2 major reading impairments; ‘alexia with agraphia’ and ‘alexia without agraphia’, related to specific cortical lesions. Alexia with agraphia was characterise by acquired deficits in reading (alexia) and writing (agraphia) that were related to lesions in the left angular gyrus. By contrast, alexia without agraphia (also referred to as pure alexia), characterised by reading impairment with intact writing ability, was associated with lesions to the left occipital cortex and the splenium of the corpus callosum, and was therefore thought to arise from a disconnection of the left angular gyrus and the visual cortex. The left angular gyrus was thus assumed to be involved in storing memories of visual word forms, an idea, which later gave rise to the concept of the *mental lexicon*; a cerebral 'database', which stores concepts of words and visual word forms represented in scattered cortical regions (rather than solely the left angular gyrus). These are connected to areas within the somatosensory junction, which link and integrate visual, auditory and somatic information from the surrounding environment (e.g. Geschwindt, 1979; Gazzaniga, Ivry & Mangun, 1998; see Coltheart, 2004 for a review).

Based on the association between cortical lesions and language impairment, Wernicke developed a model for language processing, whose general principles prevail in modern neurolinguistics. According to this model (illustrated in Fig 2-1), the underlying structure for language processing is the STG, often referred to as Wernicke's area. For language production, concepts from the mental lexicon are initially processed by the STG, transferred through the arcuate fasciculus to Broca's area – the IFG, where detailed and coordinated vocalization 'programme' is formulated. In turn, this information is transferred to the face area in the primary motor cortex (PMC), where further processing results in speech. Wernicke's account of language comprehension follows a reversed pathway, whereby auditory input is transferred from the primary auditory cortex (PAC) to the STG for coherent decoding, integrated in the IFG to form internal vocalization, which in turn is transferred to the mental lexicon for meaning retrieval (Gazzaniga et al, 1998; Price, 2000).

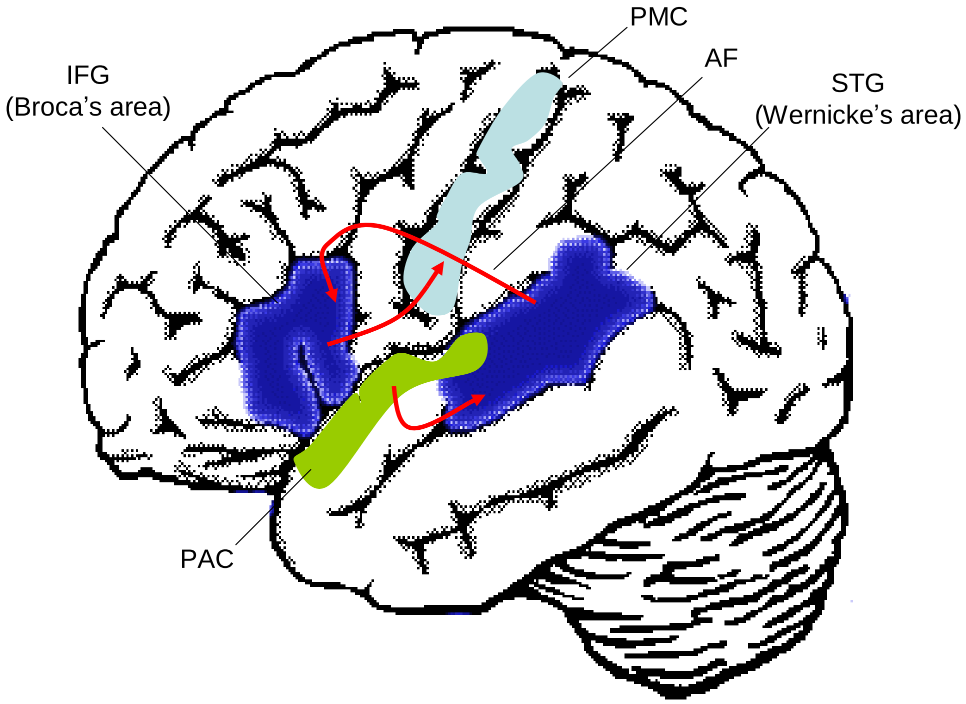

Figure 2-1 *The anatomy of Wernicke's model of language processing (adapted from Price, 2000)*
Red arrows represent information flow along white matter pathways
Abbreviations: IFG=inferior frontal gyrus; PMC=primary motor cortex; AF=arcuate fasciculus; STG=superior temporal gyrus; PAC=primary auditory cortex

Similarly, 19th century models for the process of reading (illustrated in Fig 2-2) incorporated largely the same left-lateralised regions involved in verbal language processing, as well as the visual cortex and regions around the left angular gyrus.

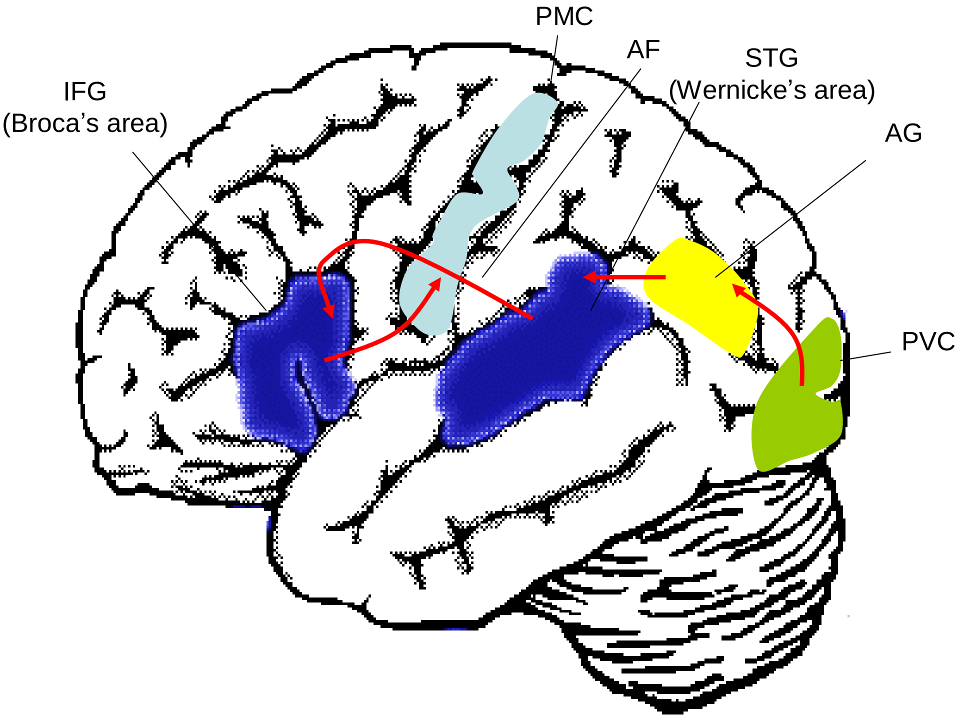

***Figure 2-2** The anatomy of 19th century models of reading (adapted from Price, 2000)*
Red arrows represent information flow along white matter pathways
Abbreviations: IFG=inferior frontal gyrus; PMC=primary motor cortex; AF=arcuate fasciculus; AG=angular gyrus; STG=superior temporal gyrus; PVC=primary visual cortex

Since the time of Broca, Wernicke and Dejerine various other types of language impairments have been defined, the majority of which have been associated with damage to left-lateralized cortical regions. For example, transcortical motor aphasia, characterised by non-fluent explosive speech with preserved comprehension, has been associated with lesions encompassing areas anterior or superior to left IFG (Dronkers, 1996). By contrast, transcortical sensory aphasia, characterised by fluent speech, with impaired comprehension has been associated with lesions to areas adjacent to left STG, the left thalamus, as well as distributed lesions to the posterior and inferior parietal cortex and white matter connecting these areas (Price, 2000). Damage to the left angular gyrus, the middle portion of the left fusiform gyrus (referred to by some as visual word form area, e.g. Cohen, Lehericy, Chochon, Lemer, Rivaud & Dehaene, 2002), and the pathways connecting these regions with the visual cortex, has been associated with various types of alexia (Geschwind, 1979; Damasio & Damasio, 1983). Similarly, damage to the left supramarginal and lingual gyri has been associated with word-finding difficulty, or anomia (Pinker, 1994).

It is remarkable that such a large body of knowledge has been gathered in those early years, relying solely on the inference of the function of cerebral structures from observed dysfunction, since cortical lesions tend to be extensive and extremely variable across patients, and may thus have differential effects on cognitive processing. Since the late 1980’s, the development of neuroimaging techniques, in conjunction with behavioural methods as well as observed deficits, have provided an invaluable opportunity to study language processing in healthy and impaired individuals *in vivo*, thus enabling a more controlled and reliable approach to gathering knowledge, particularly on the process of reading, as will be described in the next section.

2.3 To read and read not…

Explained simply, reading begins with visual identification of word forms and culminates in comprehension. Any experienced reader knows however, that when confronted with a text, the processes occurring between the initial and final stages of reading may be far from simple. Some words may be read very easily, while others may involve considerable effort and time. For example, highly familiar words, which are encountered often (high-frequency words), can be recognised very quickly, whereas rare (low-frequency) words may take considerably more time to pronounce (e.g. Forster & Chambers, 1973; Fredriksen & Kroll, 1976; Balota & Chumbley, 1984). The difference in reaction time (RT) between reading high and low-frequency words is referred to as word-frequency effect. Similarly, reading novel or nonexistent words may take significantly more time than both high- and low-frequency words, giving rise to lexicality effects (e.g. Forster & Chambers, 1973; Fredriksen & Kroll, 1976; Lukatela et al, 1989). Moreover, length effects may emerge in some cases, whereby short words may be read faster than long words (e.g. Fredriksen & Kroll, 1976; Balota & Chumbley, 1985; Weekes, 1997; Wydell et al, 2003; Juphard, Cabonnel & Valdois, 2004). Furthermore, the existence of irregularly spelled words, particularly in languages such as English, may sometimes lead to increased effort and reading time, resulting in regularity or consistency effects[1] (e.g. Glushko, 1979; Andrews, 1982; Monsell, Patterson, Graham, Hughes & Milroy, 1992).

Importantly, these effects may be inter-dependent, such that high-frequency words may be read easily regardless of their consistency or length, whereas reading of low-frequency words and novel words may become considerably slower with the decrease of consistency level, and increase of number of letters. Therefore, word-frequency and lexicality may modulate consistency effects and length effects (e.g. Andrews, 1982

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[1] The terms regularity and consistency, while in essence depicting the same phenomenon, have different implication on models of reading. Regularity is regarded as a binary characteristic, i.e. regular words follow grapheme-to-phoneme conversion (GPC) rules and irregular words do not. In contrast, consistency is a graded characteristic, whereby some irregular words are still phonologically consistent with many other orthographically similar words, e.g. hood, good; hive, chive; oat, boat (Glushko, 1979). For simplicity, the term consistency will be predominantly used throughout the thesis.

& Weekes, 1997; Juphard et al, 2004 respectively). By the same token, length effects may also be modulated by consistency of low-frequency words and non-words (e.g. Ziegler et al, 2001; de Groot et al, 2002; Wydell et al, 2003).

Cases of reading impairments, such as developmental and acquired dyslexia exemplify the complexity of the reading process. Some insight into the different processes that may operate in normal reading has come from the identification of different types of impairments and their dissociability (Marshall & Newcombe, 1973). For example, individuals with surface dyslexia may read regularly spelled words correctly, but tend to make regularization errors, such as reading the word ‘pint’ as rhyming with ‘hint’, ‘mint’ or ‘tint’. This type of dyslexia may arise as a result of impaired mediation of meaning retrieval (lexical access). By contrast, individuals with phonological dyslexia may be able to recognise familiar words regardless of their regularity, but exhibit an inability to correctly pronounce novel words and non-words, which are not represented in their mental lexicon. These individuals may read the non-word ‘motch’ as ‘match’ or the non-word ‘starn’ as ‘start’, suggesting that the impairment may lie in the process of sublexical / phonological recoding. Likewise, a third type of impairment, referred to as deep dyslexia, is characterised both by lexical and sublexical impairments, in addition to a tendency to make semantic errors, such as identifying the word ‘lemon’ as ‘orange’ (reviewed by Gazzaniga et al, 1998; Price, 2000; Price & Mechelli, 2005).

2.3.1 Cognitive models of reading

It therefore emerges that the processes involved in reading include orthographic processing, semantic processing, sublexical / phonological decoding and lexical access, and given the dissociations between different reading impairments it logically follows that separate mechanisms may mediate them. Indeed, various theories and computer-simulated models have been developed to explain how exactly these processes occur during natural reading. The two most prominent models are presented herein.

The ‘Dual-Route reading model’ (Coltheart & Rastle, 1994; Rastle & Coltheart, 1998) postulates the existence of 2 parallel mechanisms; a lexical route and a sublexical / phonological route (Figure 2-3).

The lexical route is thought of as a fast and direct process, whereby the orthographic form of whole words is accessed by the orthographic lexicon, followed either by directly addressing the whole word’s phonology in the phonological lexicon (e.g. in the case of extremely high-frequency words), or via the mediation of semantic knowledge of stored concepts (e.g. in the case of low-frequency words).

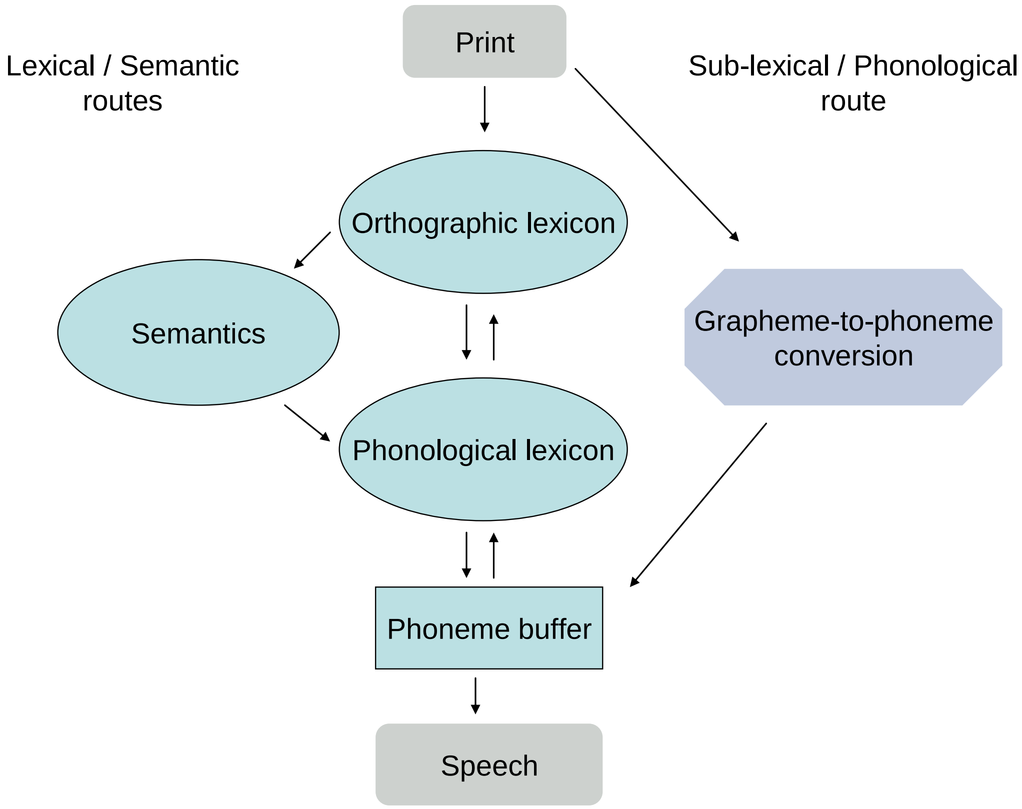

Figure 2-3 *Schematic representation of the Dual-Route reading model (after Ziegler, Perry & Coltheart, 2000)*

By contrast, the sublexical / phonological route operates sequentially along the letter string, serially transforming graphemic information into phonology (grapheme-to-phoneme conversion), thus by-passing both orthographic and phonological lexicons. This route is designed for coping with novel words, which do not have a stored lexical entry. The routes converge at the ‘phonemic buffer’, where a phonological output is prepared for articulation.

According to this model, natural reading involves the parallel activation of both routes in a competitive manner, such that the preferred route will be the first to generate the correct pronunciation to any given letter string. In the case of high-frequency words, fast and efficient naming latency is achieved thanks to the fast activation of the lexical route. However, in the case of low-frequency words, the increased time required for semantic access may allow for the activation of the sublexical phonological route simultaneously, thus creating a conflict between the two routes. In such cases, the preference for either route may be modulated by factors such as consistency and length.

For example, in the case of low-frequency inconsistent words, the use of grapheme-to-phoneme conversion would lead to regularization errors, such as those seen in surface dyslexia. The correct pronunciation of such words thus requires a “lexical lookup procedure” (Rastle & Coltheart, 2000, p.343), and the competition between the routes may lead to slower naming than that achieved for high-frequency inconsistent words. By the same token, the correct pronunciation of novel words or non-words requires sublexical / phonological recoding. Otherwise, “lexical capture” (Funnell & Davidson, 1989) as seen in phonological dyslexia would occur. However, in the case of an irregularly spelled non-word, lexical access may be inevitable. For example, the non-word ‘jough’ requires grapheme-to-phoneme conversion, followed by lexical lookup, that would lead to its pronunciation as rhyming either with ‘cough’, with ‘tough’, or with ‘dough’. Within this framework, the sublexical / phonological route may be sensitive to string-length, due to its sequential nature, such that the longer the letter-string, the more processing time required for generating a full pronunciation. In contrast, the lexical / semantic routes are not sensitive to string-length or consistency, such that reading long or inconsistent words which are frequent enough to be readily available for lexical retrieval should not involve increased processing resources.

An alternative to the Dual-Route model, the Parallel Distributed Connectionist reading model (Figure 2-4) postulates that words and non-words are all read by a single uniform mechanism based on the reader's experience (Seidenberg & McClelland, 1989; Plaut, McClelland, Seidenberg & Patterson, 1996; Plaut & Kello, 1999). According to this alternative model, reading requires the orthographic patterns of a word to generate an appropriate phonological pattern, achieved by the cooperative and competitive interactions between three types of units; orthographic, phonological and semantic units.

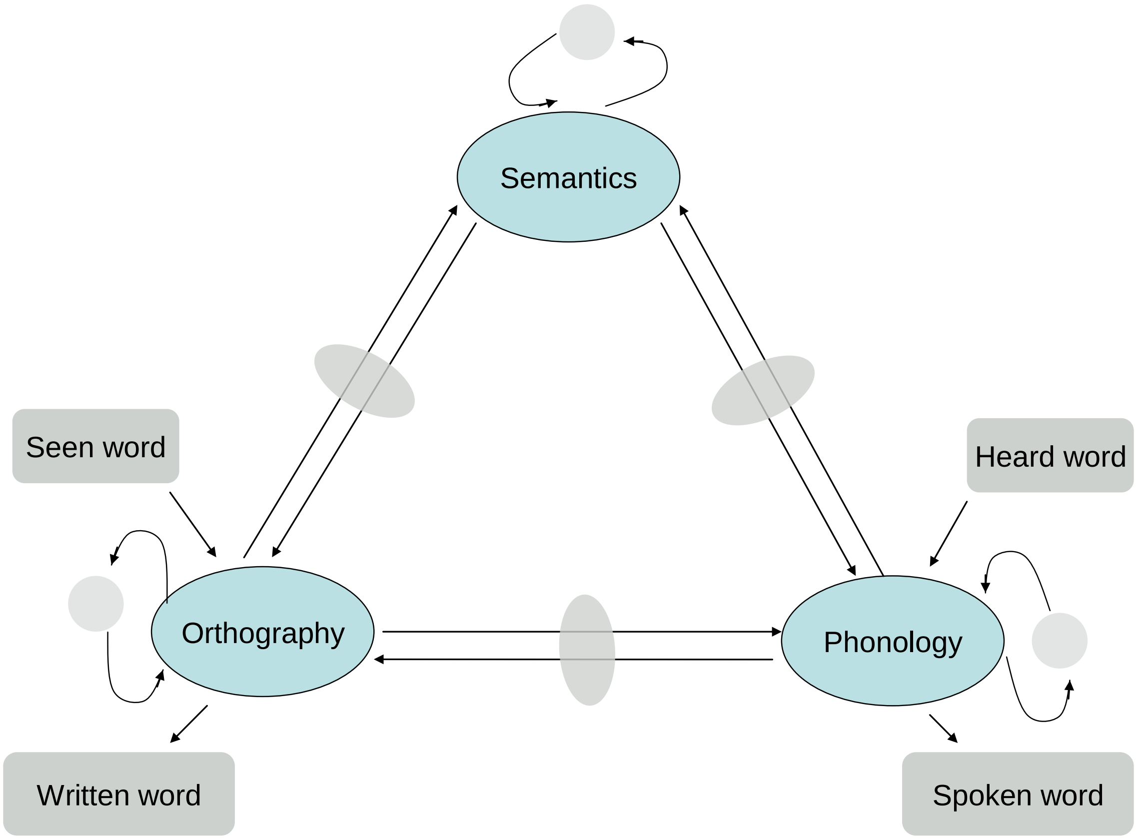

Figure 2-4 *Schematic representation of Connectionist Distributed reading model (after Plaut & Kello, 1999). Light grey circles and ovals represent 'hidden units'*

Within this theoretical framework, naming words and non-words alike occurs through a single interactive process relying on a network of weighted connections between orthography, phonology and semantics, which are sensitive to statistical relationships between “hidden” units (depicted by light grey oval shapes in the figure), constituting distributed internal representations. These internal representations are modulated by the level of visual exposure to verbal stimuli, i.e. reading experience. Orthographic, phonological and semantic units consist of two layers; a visual input, and an articulatory output, which are mediated by hidden units. When reading familiar words, the model generates an orthographic representation of the entire word, which with weighted input from semantics, is used as input for the sequential articulatory output. The weight of the semantic input may vary with exposure as well as with consistency level, such that inconsistent words require a greater semantic input than consistent words (Plaut, 1996). By contrast, in the case of novel words, the model activates a sequence of phonemes, and simultaneously monitors grapheme-position. The visual monitoring remains fixed as long as the graphemic and phonemic units are consistent. However, in the case of inconsistent novel words or non-words, the model relies on multiple visual fixations on the stimulus, virtually phoneme by phoneme, until the correct pronunciation is achieved. These processes can thus account for frequency, consistency, lexicality and length effects, and similarly to the Dual-Route model, essentially depict two procedures (rather than a single process) of visual word recognition.

Whether these procedures are activated in parallel or sequentially is still a matter of debate. Even so, evidence for their existence has come from some experimental studies with healthy participants examining the effects of different lexical factors on performance (reaction time and accuracy) in tasks such as word naming or lexical decision[2]. Based on the premise that each type of processing should leave characteristic traces on performance, it has been shown that skilled readers tend to use whole-word recognition when reading high-frequency words, whereas reading low-frequency words and non-words tends to involve the use of grapheme-to-phoneme conversion (e.g. Balota & Chumbley, 1984; Jescheniak & Levelt, 1984).

Similarly, it has been shown that consistency may affect the strategy employed by readers, such that low-frequency consistent words tend to be read using grapheme-to-phoneme conversion, whereas inconsistent words require lexical access for correct pronunciation (e.g. Andrews, 1982; Monsell et al, 1992; Jared, 1997). In addition, between-task comparisons have shown robust consistency, as well as length effects in tasks such as word naming, which explicitly require reading, relative to tasks that permit fast lexical decision without sequential processing (e.g. Andrews, 1982; Frost, Katz & Bentin, 1987; Tabossi & Laghi, 1992; Pugh Bennett, Shaywitz et al, 1996; de Groot et al, 2002; Wydell et al, 2003).

2.3.2 The neural basis of reading

More recently, findings from several functional neuroimaging studies have suggested that the dissociability between the different types of processing may be visualized at the cortical level (for comprehensive reviews see Price, 2000; Jobard, Crivello & Tzourio-Mazoyer, 2003; Price & Mechelli,

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[2] The lexical decision task requires discrimination between real words and non-words in a forced choice paradigm e.g. pressing a “YES” response button if the stimulus is a real word and a “NO” button if the stimulus is a non-word.

2005; Balota & Yap, 2006). Before reviewing examples of seminal functional neuroimaging studies on the processes of reading, it is necessary to outline the fundamental principles of this newly emerging technology, as well as its advantages and disadvantages.

2.3.2.1 Fundamental principles of functional neuroimaging techniques

As mentioned in Chapter 1, functional neuroimaging techniques enable *in vivo* visualisation of local changes in neural activity (Raichle, 1994), in response to experimental manipulation, such as cognitive tests. The development of these techniques has provided a tremendous advantage to cognitive neuroscience by enabling multiple-subject studies to be carried out with healthy participants rather than relying on case studies of neurological patients, as well as avoiding the need to rely on lesions to infer neural function from observed dysfunction (e.g. Price, 2000). The visualisation of neural activity may be defined either in terms of its time course (temporal information) or its anatomical location (spatial information), measured by the electrophysiological or hemodynamic properties of neuronal depolarisation, respectively.

Electromagnetic neuroimaging methods such as electroencephalography (EEG) and magnetoencephalography (MEG) measure electrical activity generated by neuronal depolarisation, or its associated magnetic activity, respectively, directly at the scalp. These methods can reliably map the time course of neural activation in real time (millisecond by millisecond; Okada, Mangee, Papuashvili & Chibing, 1995), though they do not provide precise information about the anatomical sources of these signals, and thus afford relatively poor spatial accuracy (Frith and Friston, 1997).

In contrast, hemodynamic neuroimaging methods such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) measure correlates of neural activity by detecting changes in regional cerebral blood flow (rCBF) or energy metabolism accompanying neuronal depolarisation. Since these hemodynamic changes are considerably slower than electrical and magnetic changes[3], these methods provide relatively low temporal resolution. However, the resulting images provide high spatial resolution, which enable the localisation of neural activity with high precision, both at the cortical level and deep in the brain (Matthews, 2001).

Since both fMRI and PET rely on factors which correlate with neural activity, experimental paradigms require the inclusion of control tasks which are matched to the experimental tasks on all modalities save the processes of interest. This yields relative values of *signal change,* which are obtained with the use of ‘subtraction methodology’ (Price, 2000), whereby the areas activated in the experimental task (e.g. silent word reading) are subtracted from areas activated in a non-linguistic baseline task. This approach eliminates from the analysis those areas which were activated in response to other cognitive processes, such as general visual processing.

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[3] Measuring blood flow as an index of neural activity results in a 5-8 second lag between the changes in neuronal activity and the associated change in blood flow (Friston, 1994).

2.3.2.2. Functional neuroimaging of reading

One of the first studies to examine the processes of reading using neuroimaging in healthy participants was conducted by Pugh and colleagues (Pugh, Bennett, Shaywitz et al, 1996). Testing 38 native English speakers using fMRI, these authors sought to isolate cortical networks associated with orthographic, phonological and lexical / semantic processes in reading using four types of judgement tasks; letter case judgement (orthographic task), non-word rhyme judgement (phonological task), semantic category judgement (semantic task) and line judgement (baseline task).

Results showed that while orthographic processing was associated with strong activation in lateral middle and inferior occipital cortex bilaterally, phonological processing was strongly related to activation within left lateral orbital, prefrontal dorsolateral and inferior frontal cortex, though some activation within these regions was also observed during the semantic task. In contrast, semantic processing was specifically associated with activation within the medial occipital cortex and left superior and middle temporal regions.

These findings therefore indicated that functional specialisation for the mediation of orthographic, phonological and semantic processing exists within the language processing network, which led the authors to propose a “sketch” of the possible architecture of some of the anatomical regions associated with reading. According to this model, initial visual processing of print recruits striate and extrastriate occipital regions, followed by mapping of featural information onto orthographic representations mediated by lateral and medial extrastriate networks. Then, various inferior frontal and temporal regions contribute to the assembly of phonological representations, and finally, access to and decisions about lexical-semantic information engages the middle and superior temporal gyri bilaterally. At those early days of neuroimaging, the authors noted that some regions known to be involved in the process of reading, such as the angular and supramarginal gyri, could not be visualised under the experimental conditions used at the time. The task of investigating reading processes within these regions and providing a more detailed account of the neural networks specifically involved in orthographic, phonological and semantic processing was therefore relayed to future studies.

Subsequently, a PET study conducted by Fiez, Balota, Raichle and Petersen (1999) aimed to extend these findings by examining the neural correlates of frequency, consistency and lexicality effects in 11 native English speakers. Using a word / non-word naming task these authors showed significant patterns of activation associated with reading in a wide number of regions including bilateral inferior and middle frontal gyri, precentral gyrus and medial frontal gyrus, bilateral superior temporal gyrus and bilateral fusiform gyrus.

Examining activation pattern in each condition showed strong activation associated with reading low-frequency words relative to high-frequency words around regions encompassing the left supplementary motor area (SMA), and the left STG. Consistency effects were detected with greater intensity, showing significant patterns of activation associated with reading consistent words bilaterally around the precentral gyrus. Reading inconsistent words was associated with left lateralized activation detected around the lateral IFG, encompassing Brodmann's area (BA) 44. Importantly, frequency by consistency interaction was robustly visualized within the dorsal left IFG and the anterior insula, encompassing BA 44/45. This pattern was associated with reading low-frequency inconsistent words relative to all other conditions, similarly to the behavioural data observed in this study. Lexicality effects were visualized with significant activation associated with reading non-words, detected around the left fusiform gyrus (BA 37), and within the dorsal IFG near BA 44/45, similar to that detected in the low-frequency / inconsistent word condition. In addition, the authors noted that the intensity of activation observed in the non-word condition was significantly greater than all other conditions, with the exception of low-frequency / inconsistent words. This finding is counterintuitive, since non-words are thought to require sublexical processing whereas low-frequency inconsistent words cannot be correctly pronounced without lexical lookup (e.g. Andrews, 1982; Monsell et al, 1992; Jared, 1997; Rastle & Coltheart, 2000). On the other hand, it is likely that low-frequency inconsistent words may be identified as non-words in some cases. The similarity in activation pattern between the two conditions was thus attributed to increased resources required for the processing of such stimuli.

The authors proposed that activation in the left STG reflected sublexical / phonological processing associated with reading low-frequency words, and activation in the precentral gyrus and SMA may be elicited as a result of sub-vocalization of the stimuli. At the same time, the inferior prefrontal cortex may underlie sublexical / phonological processing such as effortful retrieval, manipulation, or selection of phonological representations.

These findings therefore suggested that the neural correlates of consistency effects may be robustly visualized, while only subtle differences related to frequency and lexicality effects may be observed. Although extremely informative, this study did not provide a clear dissociation between lexical and sublexical processing within the inferior prefrontal cortex. A possible reason may be the chosen experimental paradigm, which may not have been sensitive enough to detect subtle changes within this large cortical region, particularly due to the relatively low temporal resolution of PET as a hemodynamic neuroimaging method.

In another study, Poldrack and colleagues (Poldrack, Wagner, Prull, Desmond, Glover & Gabrieli, 1999) employed fMRI, to examine functional specialization for lexical / semantic and sublexical / phonological processing specifically within the left inferior prefrontal cortex. These authors examined patterns of activation associated with semantic discrimination (abstract / concrete judgement), phonological processing (syllable counting of words and non-words), compared to a perceptual decision task (uppercase / lowercase decision) as baseline.,. Results showed that discriminating between abstract and concrete words (semantic task) led to significant activation in the left inferior prefrontal gyrus, encompassing Brodmann’s areas 44, 45 and 47. In addition, this task was associated with minor activation in more posterior / dorsal regions of the left inferior prefrontal cortex, in the vicinity of the precentral gyrus and SMA, which was also detected while participants performed the word-syllable-counting task (phonological task). Moreover, the non-word-syllable counting task led to activation in the inferior frontal sulcus and the dorsal aspect of the gyrus (BA 44/45), similar to that reported by Fiez and colleagues (1999).

The findings from this fMRI study thus showed distinct regions associated only with semantic processing, leading the authors to suggest that sublexical / phonological processing within the left inferior prefrontal cortex may be mediated by polymodal regions, which may also underlie processing of semantic information.

More recently, McDermott and colleagues (McDermott, Petersen, Watson & Ojemann, 2003) extended these findings. Using fMRI, these authors instructed participants to think about the relationships between semantically or phonologically related words (e.g. *tiger, circus, jungle* as semantically related words, and *skill, fill, hill* as phonologically related words), and compared the activation patterns related to these two conditions relative to a baseline condition consisting of a crosshair fixation cue[4].

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[4] Crosshair fixation cues are often used as baseline tasks in functional neuroimaging studies, though these are considered as less reliable than baseline tasks which are visually similar to the experimental task. This point will be discussed further in Chapter 4.

Results showed large overlap between regions activated in both conditions, in the occipital cortex (BA 17/18/19) and fusiform gyrus (BA 37) bilaterally, the anterior and posterior parts of the left inferior frontal cortex (BA 44/45) and the medial frontal gyrus (BA 6). Moreover, the semantic condition was associated with stronger activation within the anterior portion of the IFG (triangular part) relative to the phonological condition, and exclusive activation in a region near the left superior / middle temporal sulcus (BA 22/21). In contrast, activation in the left precentral gyrus was observed with greater intensity during the phonological condition, relative to the semantic condition. Furthermore, the phonological condition was exclusively related to activation in the left inferior parietal cortex (BA 40), and in a ventral region within the posterior (opercular) part of the gyrus (BA 6/44). These authors therefore successfully distinguished between regions involved in semantic and phonological processing within the network of cortical regions involved in visual word recognition.

Importantly, studies using languages other than English have produced similar findings. For example, Joubert and colleagues (Joubert, Beauregard, Walter, Bourgouin, Beaudion, Leroux et al, 2004), focussed on frequency and lexicality effects involved in silent reading of regular French words and non-words, relative to passive viewing of length-matched consonant strings. Results showed extensive bilateral activation in the primary visual cortex and left-lateralized activation located around the IFG and temporo-parietal cortex for all linguistic tasks, as observed previously. Reading high-frequency words relative to the control task was associated with significant activation within the left angular and supramarginal gyri (BA 39/40). By contrast, reading low-frequency words and non-words relative to control led to robust activation predominantly within the left inferior frontal cortex. The direct comparison between the sublexical and the lexical tasks revealed significantly more intense activation within the left IFG. Specifically, reading low-frequency words activated the lateral region of the left IFG (BA 44), whereas reading non-words activated more dorsal regions of the gyrus (BA 45 and 47). Importantly, directly comparing the two putative sublexical tasks showed increased activation clusters associated with non-word reading in the left angular / supramarginal gyri (BA 39/40), as well as in the left precentral and medial frontal gyri, while significant bilateral regions within the STG were associated with low-frequency word reading.

Based on these findings, the authors postulated that lexical processing may be mediated by areas around the left angular and supramarginal gyri, acting as associative polymodal regions for orthographic-to-phonological word processing[5]. Similarly to findings reported by Fiez et al (1999) Poldrack et al (1999) and McDermott et al (2003), the areas around the primary motor cortex (SMA and precentral gyrus) were suggested to subserve internal vocalization, stemming from phonological analysis related to the effort required for the recognition of low-frequency, or nonexistent words. In addition, the involvement of the left STG in the processing of low-frequency words implicates this region in sublexical /

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[5] These authors based their arguments around the early suggestion that the left angular gyrus may be the site of the orthographic lexicon (Dejerine, 1892), and therefore approached the results with the a priori assumption that this region mediates lexical / semantic processes, however, greater activation in response to non-words could also reflect sublexical / phonological processing, since as noted earlier, this type of letter string is not represented in the mental lexicon

phonological processing, and not semantic processing, as suggested by McDermott et al (2003).

In another recent study, Wydell, Vuorinene, Helenius and Samelin (2003) utilized MEG to examine the neural correlates of length and lexicality effects during reading in Finnish[6]. As mentioned above, this method provides considerably better temporal resolution than hemodynamic imaging techniques, albeit relatively less accurate spatial information. The authors compared the patterns of activation and their time course, while participants were silently reading short and long words and non-words. The two extremities of the comparison, short words and long non-words, reflected lexical / semantic and sublexical / phonological processing, respectively.

Results showed that reading all stimulus types led to early activation (within 200 milliseconds [ms] of stimulus onset) primarily within the occipital midline, with significantly stronger patterns of activation associated with reading long letter strings (words and non-words alike). After 200 ms, the activation patterns expanded anteriorly, with most significant long-sustained duration of activation predominantly (though not exclusively) located within the left superior temporal cortex. These clusters were detected in response to long non-words. In contrast, reading short words revealed little activation, detected in the left parietal cortex, in the vicinity of the angular gyrus, and right mid-frontal cortex. Interestingly,

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[6] The Finnish orthography is highly transparent, similar to Spanish and Italian, and therefore more advantageous for the examination of length effects than English. This issue is addressed in section 2.5.

length effects were predominantly observed during the early course of activation, whereas lexicality effects were only apparent at the later source clusters. These effects were observed as a systematic increase in duration of activation for each stimulus type, i.e. shortest duration associated with short words, somewhat longer duration for short non-words, longer yet for long words, and longest duration of activation associated with long non-word stimuli.

The authors therefore suggested that the combined length and lexicality effects observed within the left superior temporal region may reflect both types of processing during reading.

More recently, Booth and colleagues (Booth, Lu, Burman, Chou et al, 2006) examined the neural correlates of reading in native Chinese speakers using fMRI. The authors employed a rhyming judgement task, tapping into phonological processing, whereby participants determined whether a target word rhymed with two preceding words, and a meaning-association judgement task, tapping into semantic processing, whereby participants determined whether a target word was semantically associated with two preceding words. In this experiment the baseline task consisted of straight lines, where participants were required to determine whether the third stimulus was identical to either two preceding stimuli.

Results showed that for both linguistic tasks relative to the control task, activation was predominantly left-lateralised, with peaks of activation detected within the left inferior and middle frontal gyri, medial frontal gyrus, and bilateral occipital cortex, including fusiform gyrus. A direct comparison between the phonological and semantic tasks revealed similar patterns of activations to those observed previously (Fiez et al, 1999; Poldrack et al, 1999; McDermott et al, 2003; Joubert et al, 2004). Specifically, greater activation was detected within the posterior portion of the left inferior / middle frontal gyrus (BA 9/44 opercular part) in response to the phonological task, whereas the semantic task was associated with stronger activation within the anterior portion of the left IFG (BA 44/47, triangular part). In addition, the superior / middle temporal gyrus (BA 22/21) was more strongly activated during the semantic, relative to the phonological task, which led these authors to suggest that this region may include verbal semantic representation, as suggested by McDermott et al (2003) and in keeping with Wydell et al (2003). Moreover, the inferior parietal lobule (BA 40) was found to be more strongly activated in the semantic task, relative to the phonological task, strengthening the notion that this region may be involved in the mapping between orthography and phonology (Poldrack et al, 1999; Joubert et al, 2004).

Finally, Bick, Goelman and Frost (2008) examined the neural correlates of reading in Hebrew using fMRI, employing four different types of linguistic task. In a semantic task, participants decided whether two words were semantically related, in an orthographic task, participants decided whether two words were orthographically similar, in a phonological task participants performed a rhyming decision of two words, and in a morphological task participants were instructed to decide whether two words were derived from the same root. Activation patterns of the linguistic tasks were contrasted with a visual control task consisting of line judgements, similar to the task employed by Booth et al (2006).

Results showed that linguistic tasks, relative to the control task elicited activation within the same neural circuits identified previously in reading tasks, namely left-lateralised regions within the middle / inferior frontal cortex, occipito-temporal cortex including fusiform gyrus, inferior parietal cortex and middle / superior temporal cortex. Importantly, within the middle / inferior frontal cortex, as seen previously, the semantic task was associated with activation in relatively more anterior and inferior regions (BA 45/47) relative to the other tasks. In addition, this type of processing was associated with activation within the superior temporal cortex (BA 22/21), further strengthening the suggestion that this region can be associated with both semantic and phonological processing. The orthographic task also led to activation within this region, as well as the fusiform gyrus, and the border of the superior occipital gyrus and the inferior parietal lobule (BA 39/19). The phonological task led to preferential activation in more posterior portions of the inferior frontal gyrus (BA 46) and precentral gyrus (BA 6), while the morphological task led to preferential activation in the middle frontal gyrus, similar to Booth et al’s (2006) observation in Chinese.

Despite differences in task demands and experimental procedures, the findings from the neuroimaging studies reported above largely mirror previously reported behavioural data and suggest that some functional specialization may exist within putative language processing regions, although the different types of processing involved in reading may also be mediated by shared neural substrates, even in different languages such as Finnish, French, Chinese and Hebrew.

A plausible interpretation of the neuroimaging data is that early visual analysis of all printed material occurs within the occipital cortex bilaterally, prior to any linguistic processing, gradually engaging left occipital regions for orthographic processing. Subsequently, lexical / semantic processing may be mediated predominantly within the anterior (triangular) portion of the left inferior frontal gyrus and middle frontal gyrus, while sublexical / phonological processing may be subserved predominantly by regions located around the left precentral gyrus and the lateral aspect of the inferior frontal cortex, such as the inferior frontal sulcus and opercular part of the IFG. Areas that act as mediators between orthographic and phonological information lie within the left association cortex, such as the left inferior parietal lobule, encompassing the angular and supramarginal gyri, as well as regions around the left middle and superior temporal gyrus.

A more accurate model for the cerebral regions primarily involved in reading would therefore incorporate additional regions to those described in the 19th century model described in the previous section (Fig 2-2). Based on the synthesis of the data reported in the neuroimaging studies described above, Figure 2-5 illustrates a plausible schematic representation of those regions.

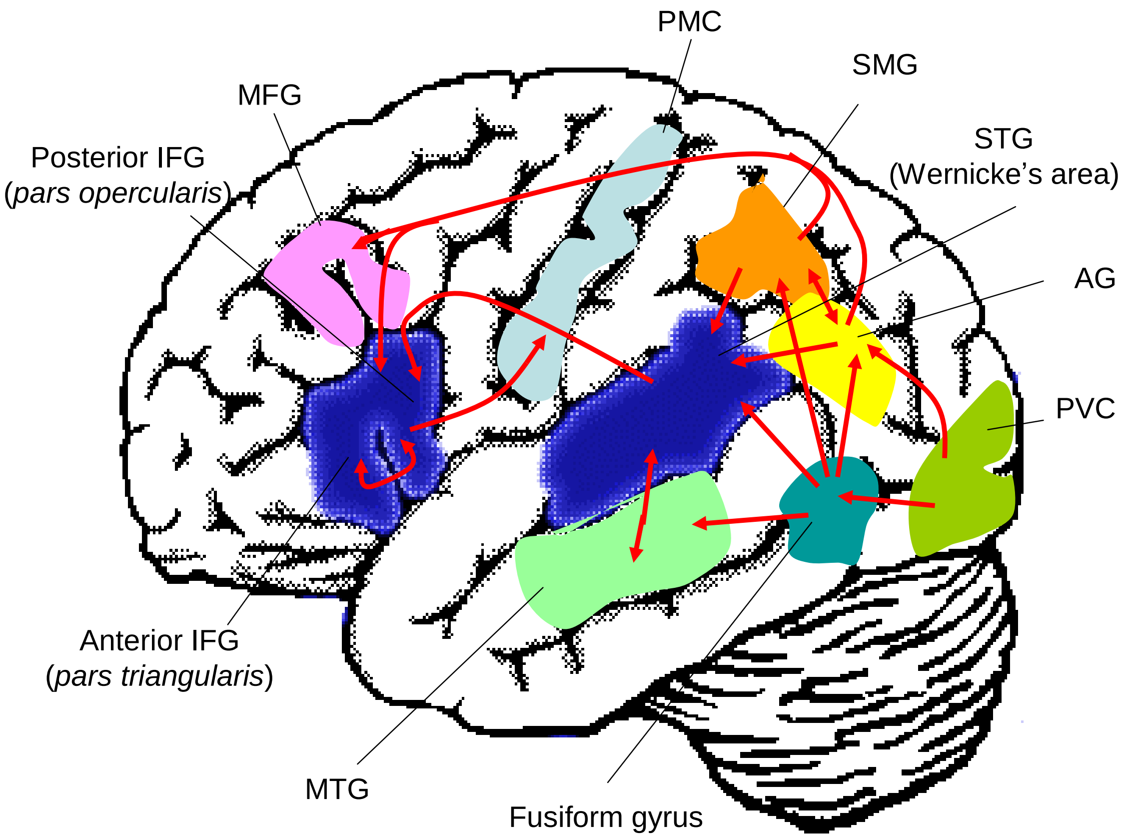

Figure 2-5 *Schematic representation of currently recognized major regions involved in reading*
Red arrows represent information flow along white matter pathways
Abbreviations: IFG=inferior frontal gyrus; MFG=middle frontal gyrus; PMC=primary motor cortex; AG=angular gyrus; STG=superior temporal gyrus; SMG=supramarginal gyrus; PVC=primary visual cortex; MTG=middle temporal gyrus

2.3.3 The role of the right cerebral hemisphere in reading

So far the focus has been on the left cerebral hemisphere. Since language processing has been repeatedly shown to be associated primarily with left-lateralised regions in neurologically intact populations, the role of the right hemisphere has been less thoroughly studied. However, aphasic patients and individuals with acquired reading disorders with left cerebral damage have often exhibited compensatory strategies recruited from right-hemisphere regions (e.g. Coltheart, 1980; Weekes, Coltheart & Gordon, 1997). Indeed, the studies outlined above have all reported activation within regions in the right hemisphere as well as the left in regular readers. Though due to the frequently observed left-hemispheric dominance, the role of the right hemisphere in reading has been rather neglected until relatively recently.

In regular readers, the role of the right hemisphere has often been investigated using the split visual field paradigm, whereby stimuli presented to the right visual field are processed in the left hemisphere and stimuli presented to the left visual field are processed in the right hemisphere. Studies employing this paradigm have repeatedly shown left visual field advantage for tasks involving orthographic and semantic processing.

For example, Chiarello and colleagues (Chiarello, Burgess, Richards & Pollock, 1990) have examined semantic priming effects to word-pairs presented to the right visual field (left hemisphere), left visual field (right hemisphere) and both (control condition). Three types of semantic relations were used; semantic category relation (e.g. animals; Deer-Pony, Cat-Dog), ordinate/subordinate relation (e.g. Bee-Honey, Music-Jazz) and a combined relation (e.g. Doctor-Nurse). Results showed strong priming effects for all semantic relation types when pairs were centrally presented. However, when presentation was lateralised, the combined relation elicited similar priming effects for both visual fields, the ordinate/subordinate relation elicited no priming effects in either fields, and the semantic category relation elicited a left visual field advantage.

These findings were taken to indicate that either cerebral hemisphere could process strongly semantically related words, while weakly related words required synergetic resources from both hemispheres. Specifically, automatic access to semantic category relatedness occurred primarily in the right hemisphere, whereas the left hemisphere was engaged in rapid meaning selection, and inhibition of semantic competitors. These authors therefore concluded that the right hemisphere was involved in coarse semantic processing whereas the left hemisphere was involved in more fine-grained processes.

More recently, Strange and colleagues (Strange, Henson, Friston & Dolan, 2000), using fMRI, found stronger activation in the right hemisphere when participants were reading semantically illogical verb-noun phrases. Similarly, Lavidor and Ellis (2002) found stronger facilitatory effects of word neighbourhood size on lexical decision when words were presented to the right hemisphere, but not to the left hemisphere, implicating the right hemisphere in semantic processing.

Having identified the regions involved in verbal and written language processing, a question that emerges with regard to the present study is: how is language represented in the brains of individuals who can speak and read more than one language? This issue is addressed in the final two sections of this chapter.

2.4 Multilingualism

Multilingualism can be defined as “the ability to speak, read or write several languages or many languages with some facility…” (The Online Medical Dictionary of the University of Newcastle; http://cancerweb.ncl.ac.uk). Since the onset of the industrial revolution in the late 18th century, transfer of knowledge across different countries has led to an increase in demand for education and for foreign language acquisition. In addition, changes in political circumstances leading to changes of international borders have led to the merging and division of different cultures and languages, to a point in which several countries around the world today are officially bilingual or multilingual. Canada, Switzerland, Belgium and India are well-known examples. Moreover, with the development of sophisticated and relatively inexpensive means of transportation, international travel, for short as well as long periods of time, has become increasingly popular in the past 50 years. These are few of several examples of factors which have resulted in the rise of multilingualism across the world and with it, the aspiration to understand this phenomenon by a myriad of disciplines, ranging from social science and education, to neuroscience and medicine.

Two of the central questions in the field of neurolinguistics have been whether the native language (L1) and additional languages (L2, L3 etc.) are represented within a common or separate mental lexicons, and whether overlapping or distinct cerebral regions are associated with processing multiple languages. These questions were fuelled by early observations of multilingual patients suffering from brain damage exhibiting symptoms of language impairment thought to be specific to multilingual aphasia (reviewed by Fabbro, 2001).

Behavioural studies conducted with bilinguals have repeatedly shown a high level of interference or competition between participants’ L1 and L2. For example, Beauvillain and Grainger (1987) conducted an experiment using a cross-language semantic priming task with French-English bilinguals. Participants made English lexical decisions on target letter-strings primed by French words. French primes were homographs[7] of English words, e.g. *coin* (meaning *corner* in French), which were either semantically related to the target e.g. *coin-money*, or unrelated e.g. *coin-house*. Results showed that lexical decisions were faster in the related condition relative to the unrelated condition, suggesting that although bilinguals were aware that primes were in French, and therefore should not interfere with lexical decision in English, the English reading of the primes induced a semantic priming effect.

Another study using the lexical decision task as an experimental tool was conducted by Van Heuven, Dijkstra and Grainger (1998) with Dutch-English bilinguals and English monolinguals. These authors manipulated the number of orthographic neighbours[8] in the two languages. Results showed that increasing the number of Dutch neighbours of English target words (i.e. the number of Dutch words that can be formed by changing a single letter in the English word) slowed down English lexical decision in the bilinguals, but not in the monolinguals.

Jared and Kroll (2001) showed similar results with phonological body neighbours[9], using a word naming task with French-English, and English-French bilinguals. In four experiments, the authors tested whether naming

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[7] Interlingual homographs are words that share the same spelling in two or more languages; homographs can be cognates, i.e. share the same meaning, or non-cognates, i.e. have different meanings

[8] I.e. the number of words in one language that can be formed by changing a single letter in another language

[9] Word body neighbours are words that share their medial vowels and final consonants, e.g. *save* and *wave.* These do not necessarily rhyme, e.g. *pint* and *mint*

a word in the target language e.g. *bait* in English was affected by the existence of body neighbours with a different pronunciation in the non-target language e.g. *lait* (milk) in French. Participants were presented with a list of English test words, which were either preceded or followed by a list of French filler words. Results showed cross-language interference, in the form of slower naming, in the French-English bilinguals regardless of the order of language presentation, whereas the English-French bilinguals showed slower RT for English words only when initially presented with the French list. Moreover, this interference was dependent on language proficiency, whereby less proficient English-French bilinguals showed less cross language interference relative to more proficient bilinguals.

Similarly, Gollan, Forster and Frost (1997) have shown cross-language interference at the phonological level even in languages of different scripts such as English and Hebrew. Using a masked translation priming task with Hebrew-English cognates and non-cognates[10], the authors showed (in Experiments 1 and 2) faster lexical decisions for L2 targets that were primed by L1 cognate translations of the targets, relative to non-cognate translations.

An interesting study conducted by Marian, Spivey and Hirsch (2003) used eye-tracking to show that Russian-English bilinguals tended to make eye-movements towards pictures of cross-language phonetically overlapping competitor objects. For example, when instructed in Russian to “pick up the stamp” (pronounced *marku*, in Russian), participants initially made

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[10] Note that in languages with different scripts, cognates share phonological and semantic characteristics, but obviously no orthographic characteristics

eye-movements towards a picture of a marker. These effects were equally significant when participants were performing the task in English, their less dominant language.

More recently, another interesting study conducted by Thierry and Wu (2004) investigated the qualitative differences between L1 and L2 processing in Chinese-English bilinguals. These authors used behavioural measures in conjunction with EEG to examine semantic priming effects in English (L2), with concealed word-form repetition in the Chinese (L1) translation of the English words. Results showed that when English word-pairs were semantically unrelated, but their Chinese translations shared logographic characters, bilingual participants exhibited slower RT's, lower accuracy levels and stronger negativities in the N400 component[11], despite being unaware of the concealed word-form repetition. These findings were taken to indicate that bilinguals may tend to unconsciously translate words into their L1 when reading in their L2. Importantly, the participants in this study were regarded as 'late' bilinguals, i.e., they had acquired their L2 at the age of 14 or 15. The authors therefore emphasised that in 'early' bilinguals these effects may not necessarily have emerged. This point will be discussed further below.

The studies described above suggest that both L1 and L2 may be represented by shared cognitive systems in bilinguals. Importantly, Lemhöfer, Dijkstra and Michel (2004) showed that this was also true for

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[11] The N400 component was chosen by the authors since it has been specifically associated with semantic and repetition priming effects (Doyle et al, 1996; Dehaene et al, 2001).

trilinguals. These authors tested Dutch-English-German trilinguals, using a lexical decision task in German (Participants' L3), using cognates, which overlapped in Dutch and German ('double cognates') or in all three languages ('triple cognates'), as well as non-cognate German words. Results showed faster lexical decision times for double cognates relative to non-cognates, and even faster responses for triple, relative to double cognates. Moreover, the triple cognate effect was not influenced by whether participants had previously been exposed to an English text.

Neuroimaging studies using various experimental paradigms and different languages have further strengthened this notion. For example, Klein et al (1994) have used *PET* to assess cerebral activation during *verb-generation* tasks in *Chinese-English* bilinguals, while Hernandez et al (2001) have used *fMRI* with 6 *Spanish-English* bilinguals, *switching* between languages using *picture-naming* tasks. Kim et al (1997) compared cortical areas of activation during *whole-sentence generation* using *fMRI*, while Perani and colleagues (Perani, Dehaene, Grassy, Cohen, Cappa Dupoux, Fazio & Mahler, 1996) have used *PET* to examine activation patterns while subjects were *listening to short stories*. More recently, Pillai, Araque, Allison, Sethuraman et al (2003) used *fMRI* to compare the neural correlates involved in *semantic and phonological processing* in *Spanish-English* bilinguals, while Halsband (2006) used *PET* with *Finnish-English* bilinguals, to examine whether *verbal memory* in these two unrelated languages was mediated by separate or a shared neural system.

These studies have repeatedly shown that multiple languages are largely represented in overlapping language-processing regions as those seen in monolinguals, with differences emerging as a result of different levels of proficiency and exposure to the different languages.

Recall Grosjean’s warning (1989): “bilinguals are not two monolinguals in one person”. Balanced multilingualism is a rare phenomenon. Currently therefore, it is generally accepted that the earlier in life a language is acquired, the higher the level of proficiency eventually attained by the user due to a greater level of cortical plasticity during early childhood (Abutalebi, Cappa & Perani, 2005). Similarly, prolonged use and continued exposure to a second language has been correlated with proficiency level (e.g. Vingerhoets et al, 2003; Briellmann et al, 2004; Moreno & Kutas, 2005), to a point which the second language may even replace the native language (Pallier, Dehaene, Poline et al, 2003; Meschan & Hernandez, 2005).

An innovative study by Mechelli and colleagues (Mechelli, Crinion, Noppeney et al, 2004), investigating structural plasticity in the bilingual brain using voxel-based morphometry, showed that bilinguals had increased grey-matter density in the left inferior parietal cortex relative to monolinguals. Moreover, these authors showed that the greater density was related to higher levels of proficiency and younger age of acquisition of L2. These results suggest that the structure of the brain may be altered by the experience of second language acquisition.

Some studies focussed on determining the functional role of language proficiency in the bilingual brain have shown that ‘early’ or highly fluent bilinguals exhibited very little difference in the areas of activation while performing tasks in different languages, while ‘late’ or less proficient bilinguals exhibited more extensive activation within overlapping regions, as well as some distinct regions, predominantly involved in working memory and attention (Perani et al, 1996; Dehaene, Dupoux, Mahler, Kim et al, 1997; Hernandez et al, 2001; Wattendorf, Westermann, Zappatore et al, 2001; Watenburger, Heekeren, Abutelabi, Cappa, Villringer & Perani, 2003), as well as some homologous language processing regions in the right hemisphere (e.g. Dehaene et al, 1997; Proverbio, Cok & Zani, 2002; Pillai et al, 2003). Others, however, have shown largely (but not entirely) overlapping neural substrates even in late bilingual subjects (Klein et al, 1994; Chee et al, 1999; Pu et al, 2001; Wattendorf, Westermann, Zappatore et al, 2003; Halsband, 2006), suggesting that even with relatively less exposure to a second language, the neural architecture of multiple-language representation may largely overlap.

Conflicting findings may be related to variance in experimental techniques, e.g., reliability of control tasks, limited sample size, modality of stimuli presentation, complexity of linguistic tasks and the underlying cognitive demands, as well as the languages under investigation (see Abutalebi & Green, 2007 for a comprehensive review). The imaging studies described above have all relied on bilingual data, since from an empirical point of view, pairwise comparisons tend to be simpler than multiple comparisons. To date, three published neuroimaging studies have attempted to extend current findings by examining multilingual participants, based on the idea that providing multiple points for comparison within the same participants would yield more reliable results.

The first neuroimaging study to include multilinguals was conducted by Yetkin and colleagues (1996). The study aimed to assess the ability of fMRI to detect changes in patterns of brain activation in multilinguals, and determine whether different levels of language proficiency may elicit differential patterns of activation. The authors examined patterns of brain activation in 5 trilinguals, native speakers of English, with varied second and third languages (German, Turkish, Norwegian, Chinese, Japanese, Russian, French and Spanish). Language proficiency was defined as “speaking the language currently for at least 5 years” (p. 473). Trilinguals performed a word generation task in their respective languages, and results showed larger foci of activation within left-lateralized language processing areas in response to the less dominant languages compared to the native language. The authors thus confirmed the adequacy of fMRI as a neuroimaging method for examining the functional organization of different languages in multilinguals, and suggested that less dominant languages may require more processing resources, which may therefore lead to increased cortical activation.

A more detailed evaluation of the issues of language proficiency was reported by Vingerhoets and colleagues (2003), who assessed the linguistic performance of 12 trilinguals of Dutch, French and English, using fMRI. Participants performed a verbal fluency task, a picture naming task, and a reading comprehension task in the three languages. The authors included behavioural measures and questionnaires to assess language proficiency, age of acquisition and level of daily exposure to each language. Similar to the findings of Yetkin et al (1996), results suggested that multiple languages were represented in overlapping language processing areas, and that processing of less dominant languages entailed more extensive cortical activation than processing of the native language. Moreover, the correlation of behavioural and neuroimaging findings suggested that the most influential factor on language proficiency was the level of exposure to the language, rather than the age of its acquisition. These findings were later replicated by Briellmann and colleagues (2004), who assessed 6 heterogeneous quadri-lingual participants on a noun-verb generation task, also using fMRI.

Taken together, current findings convey the general notion that different patterns of activation observed between different languages may be related to increased effort involved in the processing of a second (or third, or forth) language. These observations strengthen Grosjean’s argument with regards to cortical representation of general language processing and provide convincing answers to the two questions listed at the beginning of this section, i.e., whether different languages are represented in separate or shared mental lexicons, and whether distinct or overlapping neural substrates subserve their processing. But how can these observations be applied to reading in different languages? This question is addressed in the next section.

2.5 Reading in different languages

As highlighted in Chapter 1, different languages consist of various types of writing-systems, and despite the universal hierarchical patterns that unite them, the relationship between the graphemic units and their phonology is not always consistent.

Non-alphabetic writing systems such as the syllabic Japanese Hiragana and Katakana consist of morphemes, which convey a reliable phonetic representation of syllables (Wydell, Butterworth & Patterson, 1995). By contrast, logographic writing systems such as Japanese Kanji (Wydell et al, 1995) and Chinese (e.g. Fang, Horng & Tzeng, 1986) consist of ideograms, representing whole words. In these writing systems no systematic relationship exists between the orthographic and phonological elements.

Alphabetic writing systems consist of letters and letter-clusters that convey different levels of phonetic information. Semitic languages such as Hebrew and Arabic convey very little phonetic information relative to Indo-European languages such as English and French, which in turn convey considerably less information that Spanish, Italian or Greek.

As early as 1902, James Hinshelwood reported the case of a multilingual British patient, who following a stroke at the age of 34, had lost the ability to read in English. On examination one week following the stroke, the ophthalmologist noted that the patient could not read any continuous printed sentence, but was often able to pick out some words “by sight” (p.

359), particularly short and familiar ones. Long words often puzzled him, and he was not able to read them by sight, however, when allowed to spell the words out letter-by-letter the patient was often able to name them. Surprisingly, when examined in his other languages, the patient was able to correctly read whole texts printed in Greek, with very little difficulty. The physician noted that reading in Latin was somewhat less fluent, but nonetheless very close to Greek, whereas reading in French was considerably more difficult for the patient, though still more fluent than English.

More recently, Wydell and Butterworth (1999) described the case of a fluent Japanese-English bilingual, with phonological dyslexia manifested in English only, and Beland and Mimouni (2001) presented the case of a French-Arabic bilingual with acquired deep dyslexia, characterised by semantic errors predominantly in French, but translation errors only in Arabic.

These observations, similar to those seen in multilingual aphasia, suggest that different languages may be represented by distinct cerebral regions. However, having established that all languages known to an individual are represented by shared networks, and having identified the different types of processes involved in reading, the dissociability between the manifestations of dyslexia in different languages suggest that the difference may be related to the languages themselves. From this perspective, it is plausible that different levels of correspondence between orthography and phonology of different languages may affect the levels of reliance upon lexical and sublexical processing (Ardila, 1991). Indeed, even among non-impaired individuals, a prevalent observation is that reading acquisition in different languages is attained at different rates (e.g. Seymor, Aro & Erksine, 2003; reviewed by Ziegler & Goswami, 2006). For example, it has been repeatedly shown that learning to read in English, even as a native language, is a more lengthy process than learning to read in more orthographically transparent languages such as Italian (Thorstad, 1991), Czech (Caravolas & Bruck, 1993), Greek (Goswami, Porpodas & Wheelwright, 1997), Spanish (Goswami, Gombert & de Barrara, 1998), German (Frith, Wimmer & Landerl, 1998) and Welsh (Ellis & Hooper, 2001; Spencer & Hanley, 2003).

It thus logically follows that writing systems that convey a low level of orthographic transparency (such as English, Japanese and Arabic) do not ‘allow’ for sublexical processing to occur without considerable cost, and should thus predominantly entail lexical processing, whereas in those languages whose orthography is relatively transparent (e.g. Greek, Latin, German, Spanish and Czech) the optimal processing strategy would be sublexical / phonological recoding. This is the premise of the ‘Orthographic Depth Hypothesis’ (ODH; Klima, 1972; Liberman, Liberman, Mattingly & Shankweiler, 1980; Lukatela, Popadic, Ognjenovic & Turvey, 1980; Katz & Feldman, 1981), whose general principles have provided the cornerstone of the present study.

The term ‘orthographic depth’ is analogous to transparency, such that orthographies with low level of transparency are regarded as ‘deep’, and more transparent orthographies are referred to as ‘shallow’. Findings from behavioural and neuroimaging studies have supported the notion that different levels of orthographic transparency may entail distinct types of cognitive processing in different languages. The next subsection describes these studies in detail.

2.5.1 The effects of varied levels of orthographic transparency on reading strategies

2.5.1.1 Behavioural studies

Initial studies attempting to validate the ODH have compared existing findings of visual word recognition in English to Serbo-Croatian (c.f. Lukatela et al, 1980; Feldman & Turvey, 1983), and suggested that native readers of Serbo-Croatian were prone to employing sublexical / phonological assembly to a greater extent than English readers, since the shallow orthography of Serbo-Croatian allows it to occur more readily. Subsequently, a cross-language experiment conducted by Katz and Feldman (1983) compared word-naming performance and lexical decision in Serbo-Croatian versus English. Results showed that while naming latency was greater than lexical decision in both languages, the difference between the two tasks was smaller in English than in Serbo-Croatian. Similarly, including the factor of semantic priming in the experiment facilitated lexical decision in Serbo-Croatian, but not naming performance, while in English semantic priming effects did not differ between the two tasks. The inclusion of this factor stemmed from the idea that the occurrence of semantic priming effects reflects the type of processing involved in reading, such that when lexical access is the predominant strategy, strong semantic priming effects will be revealed, whereas if reading is carried out primarily via grapheme-to-phoneme conversion, naming target words should not be facilitated by semantically related primes.

These findings were therefore interpreted as to indicate that orthographic depth had a significant effect on the strategy employed by experienced readers of different languages. However, severe criticism was generated by authors who have found little or no effect of orthographic depth on visual recognition, even in comparisons of extreme orthographic depths, such as Serbo-Croatian and Chinese (Seidenberg, 1985; Seidenberg & Vidanovic, 1985).

Consequently, Frost, Katz and Bentin (1987) initiated a new wave of cross-writing system comparisons, beginning with a multilingual study examining reading strategies in three groups of native speakers of alphabetic languages placed along an orthographic depth continuum; Serbo-Croatian at the shallow end, English as the midpoint and Hebrew at the deep end. Aiming to replicate previous studies comparing Serbo-Croatian and English, the authors compared naming performance with lexical decision in each language, followed by the inclusion of semantic priming tasks.

Results showed robust lexicality effects in naming performance in Hebrew, moderate effects in English, and none in Serbo-Croatian. Moreover, the difference between naming performance and lexical decision was largest in Serbo-Croatian, smaller in English, and practically nonexistent in

Hebrew[12]. Furthermore, semantic priming effects in naming were larger in Hebrew than in English and completely absent in Serbo-Croatian. Importantly, overall performance was found to be fastest in Serbo-Croatian, somewhat slower in English, and slowest in Hebrew. These findings were taken as strong support for the ODH.

However, these too were heavily criticised and counter-argued by Baluch and Besner (1991) who examined within-language effects of semantic priming and word-frequency on naming performance in Persian; a language that includes both deep and shallow types of spelling. Results from this study suggested that the inclusion of non-words in the stimulus list encouraged sublexical / phonological assembly of print-to-sound even in deep orthographies, thus confounding the data of previous studies.

This claim was supported by Tabossi and Laghi (1992) who compared semantic priming effects in the shallow Italian orthography, and found that naming in this language was influenced by semantic relatedness only in the absence of non-words. In contrast, when non-words were included, semantic relatedness affected lexical decision, but not naming performance. Moreover, when compared with the relatively deep English orthography these authors showed that in accordance with the ODH, semantic priming elicited differences between naming and lexical decision in Italian but not in English, however, these differences disappeared in

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[12] Except for high-frequency words, where contrary to expectations, naming was 70 ms slower than lexical decision. This difference was statistically significant, but was not explained by the authors.

Italian when the stimuli required lexical knowledge for correct stress assignment.

These findings led Katz and Frost (1992) to suggest a modified version to their hypothesis, thereafter referred to as the *'weak version' of the ODH*. According to the weak version, both sublexical / phonological processing, and lexical / semantic processing can mediate visual word recognition in any orthography, though the degree to which each type is used is a function of the depth of the orthography. This modified ODH therefore revoked the initial "all-or-none" perspective, and proposed a more graded nature to the reliance upon each type of strategy.

Giving a scientific hypothesis the label "weak version" does not provoke a great deal of credibility. Indeed, Besner and Smith (1992) in an article entitled "Basic Processes in Reading: Is the Orthographic Depth Hypothesis Sinking?" have compiled a mound of evidence suggesting that the psychological operations applied in oral reading share more common mechanisms than different ones, therefore bringing forward arguments in favour of a "universal hypothesis" for reading (p. 58). However, it cannot be disputed that different languages have different orthographic properties and by that virtue only, it logically follows that different levels of reliance on different types of strategies are necessary in order to achieve fast and fluent reading.

The findings described by Tabossi and Laghi (1992) led to the notion that during normal reading of shallow and deep orthographies alike, the most efficient strategy is fast lexical retrieval, which should thus predominate over the sublexical / phonological assembly so long as the orthography allowed it. Orthographic depth may thus influence the type of reading strategy only in “special conditions” (p. 309), such as when reading unfamiliar words, where visual lexical access is slower, giving way for sublexical assembly of phonology from print using grapheme-to-phoneme conversion rules. This suggestion has been supported by reported cases of deep and surface dyslexia and dysgraphia in speakers of languages with relatively shallow orthographies, such as Spanish (e.g. Ruiz, Ansaldo & Lecours, 1994; Iribarren et al, 2001) and Hindi (e.g. Ratnavalli et al 2000; Karanth, 2002).

A new debate therefore emerged, contesting the issue of which of the two processes may assume the ‘default’ role during visual word recognition in different writing systems. Critics of the ODH have postulated the so called *Visual Encoding Hypothesis*, suggesting that the most efficient strategy for reading all writing systems is lexical / semantic processing, rather than sublexical / phonological assembly of print onto sound (e.g. Seidenberg, 1985; Baluch & Besner, 1991; Tabossi & Laghi, 1992). This hypothesis supported the premise that addressed phonology, used for reading high-frequency words or inconsistent words, is faster than phonological assembly, which due to its sequential nature, requires more processing time (Rastle & Coltheart, 1994).

In contrast to the visual encoding hypothesis, the *Phonological Hypothesis* suggests that the default strategy of the cognitive system is phonological recoding, based on findings showing the use of sublexical / phonological assembly in shallow orthographies (e.g. Katz & Feldman, 1983; Frost, Katz & Bentin, 1987; Tabossi & Laghi, 1992). This hypothesis, derived from the modified, weak version of the ODH argues that “if the reader can successfully employ pre-lexical phonological information, then it will be used first; the easier it is, the more often it will be used” (Frost, 1994, p. 119).

In light of contradicting accounts, Frost (1994) conducted a within-language / between orthography study in Hebrew, similar to Baluch and Besner’s (1991) investigation of Persian. In a series of 4 elegant experiments, Frost demonstrated that experienced Hebrew readers, who would normally not rely on phonetic information to read this deep orthography, were inclined to turn to grapheme-to-phoneme conversion when diacritical marks were present. In the first experiment of this study it was shown that lexical decision and naming of shallow pointed Hebrew words were significantly affected by word-frequency and lexical status, relative to deep unpointed words. In the second experiment, semantic priming facilitated naming in the deep unpointed orthography relative to the shallow pointed orthography even in the absence of non-words in the stimulus list, thus contradicting previous claims of data being influenced by the inclusion of non-words (Baluch & Besner, 1991). In the third and fourth experiments participants were presented with consonant strings followed by diacritical marks, appearing at different stimulus onset asynchronies. The delay of presentation of diacritical marks significantly slowed naming and lexical decision, even when words could have been named unequivocally using the lexical strategy.

These findings contradicted the Visual Encoding Hypothesis, and suggested that the default reading strategy for visual word recognition may be sublexical / phonological assembly, rather than visual lexical access. Frost noted that these recent observations were in keeping with previous findings of extensive sublexical / phonological recoding in languages of shallow orthographies such as Serbo-Croatian (Lukatela et al, 1980; Feldman & Turvey, 1983 Katz & Feldman 1983), as well as languages of relatively deep orthographies such as English (e.g. Van Orden, 1987; Van Orden, Johston & Hale, 1988).

In a second study, aiming to extend these findings, Frost (1995), manipulated the levels of ambiguity of Hebrew words, and showed significantly faster naming latency for unambiguous words than for those that could be correctly pronounced in more than one way. This was coupled by a strong frequency effect, which disappeared when the words were rendered completely transparent by the inclusion of diacritical marks. The manipulation of the levels of ambiguity in Hebrew reflected the amount of missing phonological information necessary for successful assembly of phonology from print, and thus permitted the assessment of lexical involvement in naming. The results suggested that lexical access occurred whenever a complete sublexical representation could not be assembled with the use of grapheme-to-phoneme conversion. Frost therefore argued that if the reader could successfully assemble a sublexical representation from print, then the sublexical / phonological strategy would be used first. However, in the event of complex or inconsistent phonemic representations conveyed by the orthography, such as irregularly spelled words, this route would be bypassed, giving way to visual processing and direct retrieval from the mental lexicon.

A more recent study conducted by Paulesu and colleagues (Paulesu, McCrory, Fazio, Mononcello, Brunswick, Cappa et al, 2000) provided further support for the modified ODH with an original experimental paradigm. These authors used behavioural measures in conjunction with PET, to show clear differences in the types of processing involved in reading English and Italian. The behavioural experiment compared word and non-word naming in two groups of 36 native speakers of each language. Each group named high-frequency regular words in their respective native language, high-frequency international words common to both languages, and two sets of non-words, derived from either English (e.g. marnet, connage, afton) or from Italian (e.g. ponda, moco, corla). Results showed that Italian readers were overall faster than their English counterparts at naming both words and non-words, although Italian-derived non-words were named faster than those derived from English. In contrast, the English readers showed no difference in naming latency between the two types of non-words. In keeping with previous behavioural studies (Katz & Feldman, 1983; Tabossi & Laghi, 1992; Frost, 1994) the authors suggested that English readers were more prone to rely on lexical / semantic strategies during reading this “quasi-regular” orthography, than their Italian counterparts, who exhibited more extensive use of grapheme-to-phoneme conversion.

An effect that has not been examined in the studies mentioned above is the length effect. According to the prediction of current reading models, length effects emerge as a result of increased activation of the sublexical / phonological route (e.g. Rastle & Coltheart, 1998) or multiple visual fixations on unfamiliar and/or inconsistent words (Plaut & Kello, 1998). Indeed, authors examining length effects on naming performance have utilized relatively transparent languages such as Dutch (e.g. Hudson & Bergman, 1985), Finnish (e.g. Wydell et al, 2003) and German (Ziegler et al, 2001), where length effects are more likely to emerge than in relatively opaque languages such as English or Hebrew.

A relatively recent cross-language study conducted by Ziegler et al (2001) investigated length and body-neighbourhood effects on naming words and non-words in native German and native English speakers. This study utilized cognates in the two languages; such that the majority of the stimuli were orthographically and semantically identical (80% of word stimuli and 62% of non-word trials were orthographically identical). The advantage of this type of comparison lies in the contrasting levels of orthographic transparency despite the common Germanic origin of the languages. Results showed significantly stronger length effects in the native German speakers, particularly for non-word naming, relative to their English counterparts, and stronger body-neighbourhood effects in the native English speakers, relative to their German counterparts. The authors concluded that orthographic transparency of the languages in question affected the type of processing routinely involved in reading in each language, but rather than the relative *amount* of each type of processing, it was suggested that it was the “*very nature*” of these processes that differed as a function of orthographic transparency (p.379).

Taken together, the findings described above suggest that readers of shallow orthographies normally rely on sublexical / phonological assembly of sound from print, since the transparency allows for this strategy to reliably operate on small linguistic units, such as graphemes to generate a fast and efficient pronunciation. In contrast, readers of deep orthographies are forced to rely on a variety of complementary strategies, to compensate for the inability to sublexically decode the opaque print. That however, does not preclude the use of visual analysis of larger linguistic units such as whole words in shallow orthographies, as long as this strategy is more efficient than grapheme-to-phoneme conversion.

Further support for this suggestion has recently come from an elegant and very complex study, examining the effects of orthographic transparency on reading acquisition in Japanese, Albanian, Greek and English children (Ellis, Natsume, Stavropoulou, Lorenc et al, 2004). These children, aged between 6 and 15 years, read words aloud in the transparent syllabic Japanese Hiragana, in alphabetic languages of graded levels of orthographic transparency; Albanian, Greek and English, and the orthographically opaque Japanese Kanji. The authors analysed response accuracy, naming latency and error types in each language. Results showed a direct relationship between orthographic transparency and accuracy, whereby overall level of accuracy in Hiragana (90%) was higher than, in turn, Albanian (87%), Greek (85%), English (80%) and Kanji (70%).

With regard to naming latency (Albanian not included), results showed that among the younger children (6-11 years) overall naming latency was initially slowest in Greek (1600 ms), faster in Hiragana (1200 ms), and fastest in English (950 ms), with a systematic decrease as a function of age (older children achieving faster naming), which, by age 11, reached an equal level in all 3 languages (800 ms). Among the older children (11-15 years), no significant differences were seen in naming latency between the 3 languages, as well as the opaque Kanji, which was only tested among these older children. Importantly, naming latency was found to be linearly related to word-length, such that longer words were associated with slower naming, particularly in the more transparent orthographies. Specifically, regression analysis showed that naming latency for correct responses was predicted by word-length in Hiragana (60%) to a greater extent than, in turn, Greek (38%), English (36%) and Kanji (6%). The slower naming in the more transparent languages by younger children was taken as evidence for use of phonological assembly by beginner readers, who gradually, with experience learned to efficiently retrieve familiar words using lexical and semantic cues. Moreover, the linear relationship between naming latency and word-length in all age-groups supports the view that in more transparent orthographies, greater reliance on phonological assembly leads to stronger length effects than in more opaque orthographies.

Analysing the types of errors made by the children further supported this view. Previous research on the types of errors made by learners of transparent and opaque orthographies had shown that reliance on sublexical / phonological recoding strategies generated mispronunciation errors, which often led to naming real words as non-words (e.g. Wimmer & Hummer, 1990; Ellis & Hooper, 2001), whereas reliance on lexical / semantic strategies led to visually similar, real-word substitution errors (e.g. Seymour & Elder, 1986; Stuart & Coltheart, 1988). Concordantly, in this study the authors observed that non-responses accounted for 1% of all Hiragana trials, 2% of Albanian trials, 14% of Greek, 22% of English and 66% of Kanji trials. Similarly, whole-word substitution errors were most prevalent in Kanji (69%) and least prevalent in Albanian (31%). The authors interpreted the high proportion of non-responses and whole-word substitution in the opaque orthographies as an indication of lexical / semantic strategy for word identification. In contrast, non-word-like mispronunciations were highest in Albanian (68%) and lowest in Kanji (11%), suggesting that children learning to read transparent orthographies tend to assemble new words by means of grapheme-to-phoneme conversion rules. Indeed, a close examination of this type of errors showed that children tended to mix correct word segments with substitutions, gaps or misorderings, resulting in non-words.

Taken together, the findings of this elaborate study provide strong support for the (weak) ODH, suggesting that experienced and beginner readers of transparent orthographies tend to rely predominantly on sublexical / phonological assembly strategies, particularly for reading infrequent and novel words, whereas readers of opaque orthographies tend to rely predominantly on visual, lexical and semantic cues for word identification.

It is important to note that these studies have all been conducted with native monolingual speakers of the languages in question. As a result, while the within-language between-writing system studies have had the advantage of comparing the effects of different conditions within the same participants, the cross-language studies have had to rely on the less reliable between-subject comparisons. In this respect, an optimal experimental group could be bilinguals or multilinguals who were highly proficient in all the languages under investigation. However, since balanced multilingualism is a rare phenomenon, language proficiency must always be taken into account. As outlined in section 2.4, this type of comparison has been extensively used, but surprisingly, few studies have focussed on the effects of orthographic transparency on reading in bilinguals and multilinguals, looking at alphabetic languages.

An elaborate study reported recently by de Groot et al (2002) provides a thorough examination of naming and lexical decision performance in a group of Dutch-English bilinguals. These authors investigated the effects of several variables on performance in the two languages, including word-frequency, string-length, cognate status and semantic definition accuracy.

Results resembled those reported in previous studies, showing overall faster performance and more robust between-task differences in the transparent Dutch orthography relative to the opaque English. Similarly, robust frequency and semantic effects were observed in English relative to Dutch. Moreover, strong cognate effects were observed in lexical decision and naming in English, while in Dutch these effects were weak, and apparent only in naming. However, contrary to previous findings, and to the authors' predictions, length effects were more pronounced in English naming and lexical decision than in Dutch.

In a post-hoc analysis, the authors noted that a frequency by length interaction was present in English, indicating that length effects were most robust for English low-frequency words. However, no such interaction was observed in Dutch. This surprising finding led the authors to conclude that the lack of interaction in the shallow orthography had stemmed from a language proficiency effect in this bilingual group, whose native language was Dutch, and second language was English. The confounding variables of orthographic transparency and language proficiency could have been compensated had the authors included a second group of bilinguals, whose native language was English and second language was Dutch.

2.5.1.2 Neuroimaging studies

Reported neuroimaging studies focussed on reading in alphabetic writing systems with contrasting levels of orthographic transparency are surprisingly few. Within these few, some conflicting findings have emerged.

For example, Illes and colleagues (Illes, Francis, Desmond, Gabrieli, Glover, Poldrack et al, 1999) have used fMRI with a similar paradigm to that described in their monolingual study (Poldrack et al, 1999). These authors compared semantic processing (discrimination between abstract and concrete words) relative to non-semantic processing (discrimination between upper and lower case print) in a group of 8 highly proficient Spanish-English bilinguals. Similarly to the monolingual English study, the authors showed significant differences in patterns of activation within the left IFG (BA 44, 45, 47) between the semantic and non-semantic tasks, however, clear between-language differences were not found.

The authors thus concluded that a common neural system mediates semantic processing in the bilingual brain. Furthermore, relying on previous suggestions that the semantic task may also involve sublexical / phonological processing to some extent (Poldrack et al, 1999), the authors briefly discussed the possibility that anterior regions of the IFG may subserve lexical / semantic processing whereas posterior regions may be involved in sublexical / phonological processing. However, the two languages examined in their bilingual study were said to have common phonological structures, and therefore shared cortical representations. No mention was made of the behavioural studies that have found clear differences in lexical and sublexical processing associated with reading in languages whose level of orthographic transparency was similar to Spanish, relative to the less transparent English.

The first study to show cross-language differences at the cortical level with alphabetic writing systems was that conducted by Paulesu and colleagues (2000). Using PET, these authors compared the activation patterns associated with reading words and non-words in English and Italian by two groups of 6 native speakers of each language, similarly to the behavioural experiment reported in their study, described earlier.

Results were in keeping with previous and subsequent neuroimaging studies examining activation patterns associated with reading, showing extensive activation within putative language processing regions in the left hemisphere, with non-word reading in both languages associated with more robust activation relative to word reading (e.g. Fiez et al, 1999; Poldrack et al, 1999; Wydell et al, 2003; Joubert et al, 2004). Regions associated with reading English were detected with greater activation within the left posterior inferior temporal cortex (BA 21/37) and anterior portion of the left IFG (BA 45). By contrast, regions associated with reading in Italian were observed predominantly within the left superior temporal gyrus (BA 22/21). The findings from this study not only provided evidence that the level of orthographic transparency of different languages affected the preferred strategy adopted by readers, but also suggested that this preferred strategy may also affect the reading patterns in other languages, implying that bilinguals or multilinguals may employ the default strategy of their native language to read in their less dominant languages.

Indeed, much interest has been generated on the issue of whether processing of a second language may be modulated by the orthographic properties of the native language. Several behavioural studies aiming to address this issue have employed extreme ends of the orthographic transparency continuum, such as Chinese and Japanese Kanji. While some have shown that bilinguals may transfer reading strategies from their native language to their second language, others have shown similar reading processes in different languages among bilinguals.

For example, Muljani, Koda and Moates (1998) have shown that native readers of the transparent Indonesian performed better in an English (L2) lexical decision task than native Chinese readers, with equivalent level of English proficiency. Similarly, Wang, Koda and Perfetti (2003) showed that native readers of the transparent Korean tended to make errors on a semantic categorisation task in English, where items were homophones of category exemplars (e.g. category: *'flower'*, homophone: *'rows'*) whereas native readers of Chinese tended to respond accurately on this task. In contrast, on a phoneme deletion task, Chinese readers performed more poorly than Korean readers, and made more errors that were phonologically incorrect but orthographically acceptable. These authors thus concluded that Korean readers relied primarily on phonological information for reading in English, whereas Chinese readers tended to rely more on orthographic information. However, Akamatsu (2002) showed that bilingual readers, native speakers of Chinese, Japanese and Persian displayed similar word-recognition procedures for English high-frequency words, low-frequency consistent words and low-frequency inconsistent words.

Similarly, some authors have identified distinct cortical regions, such as the left middle frontal gyrus, associated with reading in such profoundly different languages, (e.g. Nakada, Fujii & Kwee, 2001; Valaki, Maestu, Simos, Ishibashi, Fernanadez, Amo & Ortiz, 2003; Lee, Tsai, Kuo, Yeh, Wu, Ho et al, 2004; Siok, Perfetti, Jin & Tan, 2004). Moreover, some have proposed the implication of right-hemisphere areas in reading logographic scripts relative to English or Spanish (e.g Tan, Feng, Fox, & Gao 2001; Liu & Perfetti, 2003; Ding, Perry, Peng, Ma, Li, Xu et al, 2003; Valaki et al, 2004). However, within that sphere, alphabetic writing systems have been rather left at bay.

Two recent neuroimaging studies have examined the effects of orthographic transparency on reading strategies in bilinguals, using alphabetic languages. First, Meschyan and Hernandez (2005) assessed the effects of language proficiency and orthographic transparency of English and Spanish on bilingual word recognition using fMRI. These authors tested early Spanish-English bilinguals, who were more proficient in their L2 (English) than in their native language (Spanish). The authors aimed to dissociate between the effects of age of acquisition and language exposure, by showing that the less proficient albeit native language would be associated with more extensive activation within a shared network of regions for both languages, as well as some activation within distinct regions, predominantly associated with sub-articulatory processes and working memory, reflecting a greater load on processing resources of the less practiced language. In addition, the authors aimed to distinguish between regions associated primarily with phonological processing and those associated primarily with semantic processing, by showing that the former would be activated preferentially for the more transparent Spanish, whereas the latter would be associated with the more opaque English, despite the varied levels of language proficiency.

Behavioral results of this study showed that participants were slower at reading Spanish relative to English, which could either be attributed to the superior proficiency of English, or the higher level of transparency of Spanish, which led to a greater reliance on phonological recoding, or a combination of these factors. The neuroimaging results clarified this by showing that Spanish was associated with more extensive activation in regions implicated in working memory and articulatory motor processes, namely the SMA, cingulate gyrus and insula, as well as preferential activation within regions associated with phonological processing, such as the left STG (BA 22) and precentral gyrus (BA 6). In contrast, reading in English was shown to preferentially activate regions associated with semantic processing, namely within occipito-parietal cortex and inferior parietal lobule (BA 40).

The authors thus concluded that while language proficiency had a profound effect on the cortical organization of language representation, orthographic transparency was less affected by language exposure, and therefore strategies employed for reading in languages with different orthographic properties were not bound to be transferred from the dominant language to the less practiced language.

Soon afterwards, Simon and colleagues (Simon, Bernard, Lalonde & Rebaï, 2006) investigated the effects of orthographic transparency on reading strategies in French and Arabic using EEG. In this study French was considered as the transparent orthography relative to the opaque Arabic, and therefore was expected to be associated with activation around the N320 component (activation detected within 320 ms of stimulus onset, which has been associated with grapheme-to-phoneme conversion in languages of relatively low level of orthographic transparency such as French [Bentin et al, 1999], relative to more transparent languages such as Italian, where earlier components have been found, such as P185 [Proverbio et al, 2004]). These authors tested Arabic-French bilinguals and French monolinguals on a bilingual lexical decision task.

Behavioural results showed that both groups, reading in their native languages achieved similar levels of accuracy and response latency. However, the French monolinguals were faster and more accurate than their bilingual counterparts, performing lexical decisions in their L2, an effect which could have risen as a result of language proficiency, despite the reported high level of exposure and early age of L2 acquisition. The electrophysiological results clarified this issue by showing clear N320 amplitudes, most notably around the posterior region of the left temporal cortex, present in both groups while making lexical decisions in French, but not in Arabic. These results, similar to Meschyan and Hernandez (2005), therefore suggested that the level or orthographic transparency was more influential for the processes of visual word identification than either age of acquisition or language exposure.

These two studies were pioneering with regards to utilising neuroimaging to investigate the effects of orthographic transparency on the patterns of activation associated with reading in alphabetic languages. Meschyan and Hernandez's (2005) contribution was important in showing that language exposure was more significant than age of acquisition as far as processing resources were concerned, as well as demonstrating that orthographic transparency was more influential than either factors on the predominant strategy used for reading in Spanish and English. Simon et al (2006) showed that the orthographically transparent French could be associated with amplitudes reflecting phonological recoding, within regions associated with that type of reading strategy, relative to the opaque Arabic. However, they did not show a clear pattern that could be associated with reading in Arabic. In this respect, fMRI would be a more efficient method than EEG. Moreover, neither one of these studies examined the strategies involved in reading the languages under investigation in detail. Indeed, to date, the only neuroimaging study that has attempted to map reading strategies used for alphabetic languages less transparent than English was that conducted using Hebrew by Frost's group (Bick, Goelman & Frost, 2008).

Taken together, the studies outlined above have shown that although the predominant strategy for reading in orthographically transparent languages involves a high level of phonological recoding using grapheme-to-phoneme conversion, lexical and semantic processing of larger linguistic units has also been shown, similar to reading in languages of opaque orthographies. Similarly, the opposite has been observed for orthographically opaque languages, whereby the predominant use of lexical and semantic processing could be substituted by phonological processing under certain circumstances. Importantly, behavioural evidence has suggested that the level of orthographic transparency of the native language may have an effect on the strategies employed by bilinguals and multilinguals while reading in their less dominant languages. More research is required in order to map the extent to which each strategy may be used in different languages at the cortical level, and to what degree, if any, does the level of orthographic transparency of the native language influence the strategies used for reading in a second language.

The present study uses three alphabetic languages, whose orthographic properties can be viewed as placed along a continuum of orthographic transparency. These are described below.

2.5.2 The Spanish orthography

Spanish alphabet is classified as a phonemic writing system. As highlighted in Chapter 1, written Spanish conveys a near one-to-one relationship between orthography and phonology, such that each written vowel can be correctly pronounced in only one way, with very few exceptions. The letter ‘U’ assumes a silent role when preceded by a ‘Q’ or a ‘G’, and the letter ‘Y’ only acts as a vowel when in conjunction with other consonants. Basic orthographic rules apply in the few cases where the grapheme-to-phoneme relationship is not entirely consistent. For example, the letter ‘X’ can be pronounced as /s/ (*xilófono)*, as /ks/ (*examen*), and as /h/ (*México*), and the letter ‘R’ is pronounced as /rr/ when positioned in the beginning of the word, or after an ‘N’ (Iribarren, Jarema & Lecours, 2001). In addition, basic rules govern stress assignment of polysyllabic words, such that all words ending with a vowel, an ‘N’ and an ‘S’, receive stress on the penultimate syllable, and words ending in all other consonants receive stress on the final syllable. In cases of exceptional words, the correct stress is marked by an accent above the corresponding vowel, e.g. *corazón* (*heart*). Non-native readers who are familiar with the script are almost always able to correctly pronounce words without necessarily understanding their meaning. Spanish orthography can thus be placed at the transparent end of the orthographic transparency continuum.

2.5.3 The English orthography

The English alphabet is classified as a morpho-phonemic writing system, since it incorporates both phonemic and morphological properties (Chomsky & Halle, 1968). As outlined in Chapter 1, in the English orthography, a relatively small number of graphemes represent a relatively large number of phonemes, and while many words do convey a one-to-one relationship between orthography and phonology, e.g. *cat, desk, scalpel*, many other words convey the original etymological root, or morpheme, e.g. *heal* and *health*, *muscle* and *musculature*, *sign* and *signature*, which are not pronounced according to phoneme-based rules as Spanish words are. Reading in English therefore requires knowledge of the spelling of whole words, or memory of appropriate context-dependent pronunciation rules.

2.5.4 The Hebrew orthography

The Hebrew alphabet consists of 24 consonants and no vowels. Instead, vowel sounds are signified by ‘diacritical marks’: points and dashes, which are typically placed below or beside consonants to indicate the correct phonetic pronunciation. When vowelised, the Hebrew orthography is almost entirely transparent. However, diacritics are used predominantly in children’s books, poetry, or Biblical scripts, and are omitted in everyday texts such as literature, press and correspondence. The prime characteristic of Semitic languages is the triconsonantal root, whereby all words are comprised of roots formed of three (and sometimes four) consonants, which are embedded in template morpho-phonological word-patterns. Both roots and word patterns are abstract constructs, whose joint combination forms specific words, though the meaning of these is usually obscure due to the absence of vowel letters.

To illustrate with an example, the combination of the root ח-ש-ב (X-SH-V) and the phonological pattern *A*A*A (asterisks represent the position of root consonants) give rise to the Hebrew word *מחשבה* (*MAXSHAVA*; *thought*). This particular root refers to anything related to the concept of thinking, while the phonological pattern represents nouns which are products of the action specified by the root. The same root can be combined with the phonological pattern *I*U*, to form the word *חישוב* (*XISHUV*; *calculation*). Moreover, this same root can also be combined with the phonological pattern *A*A* to yield the word *חשב* (past tense, singular, masculine form of *to think*). This phonological pattern often conveys past tense singular forms of verbs, but can also convey the morpho-syntactic information that the word is a noun which signifies a profession. The word *חשב* therefore, also means *accountant*. When vowelised, the verb and the noun can be easily distinguished, however, in the quotidian, unvowelised form; the appropriate meaning of the word may be extracted only when placed in context within a sentence (c.f. Benuck & Peverly, 2004).

It is important to note that although the vowelised form of Hebrew is highly transparent, the non-vowelised form is not entirely opaque. Four consonants of the Hebrew alphabet play the dual-role of ‘mothers of reading’, whereby these graphemes can signify either consonants or vowels, depending on their position within the word (much like the letter ‘Y’ in English). Mothers of reading can assume any one of the 5 spoken vowels, rendering some words highly ambiguous. For example, the letter ‘ו’ (‘VAV’) represented the vowel /u/ in the word *חישוב.* However, in the letter combination דוד (‘DALED’ ‘VAV’ ‘DALED’), the letter ‘VAV’ may represent the consonant /v/, as in the name ‘David’, or the vowel /o/, in the word ‘*DOD*’, meaning *uncle* (see Navon & Shimron, 1984 for a detailed review of Hebrew orthography).

The non-vowelised form of Hebrew is similar to the recent phenomenon that has emerged with the use of text messages in mobile phones, whereby “*wrds cn b wrttn wtht vwls nd th rdr cn stll xtrct th mnng”* with considerable effort! Therefore in the framework of the present study, Hebrew can be placed at the opaque end of the orthographic transparency continuum.

The following chapters report five experiments. Experiment 1 aimed to replicate and extend the findings of the initial cross-language naming experiment conducted by Frost et al (1987), by examining the reading strategies employed by proficient bilinguals of Spanish and English and of Hebrew and English, compared to English monolinguals. Experiment 2 was subsequently designed in order to validate an outstanding issue observed while reading in Hebrew. Then, Experiments 3 and 4 examine the neural correlates of the reading strategies involved in reading in the three languages by the same bilinguals and monolinguals, using fMRI. Finally, Experiment 5 was aimed at completing the picture by behaviourally examining the reading strategies employed by proficient trilinguals of the three languages.

Chapter 3

Re-emergence of the Orthographic Depth Hypothesis

3.1 Experiment 1:
Naming words and non-words in Spanish, English and Hebrew

3.1.1 Introduction

Despite severe criticism, the modified version of the Orthographic Depth Hypothesis has been extensively relied upon to account for differences observed in reading patterns among native and non-native speakers of different languages consisting of writing systems that convey different levels of correspondence between orthography and phonology. Indeed, many recent studies have used alternative terms to describe orthographic depth, such as ‘transparency’ (Wydell et al, 1999; Meschyan & Hernandez, 2005; Simon et al, 2006), ‘consistency’ (Jared et al,1990; Wydell et al, 1995; Fiez et al, 1999; Paulesu et al, 2000) and ‘regularity’ (Andrews, 1982), while some have also continued to use the term ’depth’ (Caravolas & Bruck, 1993; de Groot et al, 2002; Benuck & Pevery, 2004, Lemhöfer et al, 2004; Ellis et al, 2004). Since the study published by Frost, Katz and Bentin in 1987, there have been numerous publications of studies attempting to argue against (e.g. Baluch & Besner, 1992; Tabossi & Laghi, 1992), and argue for (e.g. Katz & Frost, 1992; Frost, 1994; 1995) the hypothesis. However, no reported study has attempted to replicate and extend the initial cross-language investigation, which led to its proposal in the first place.

In addition, it has been suggested that in bilinguals, the optimal strategy used for reading in the native language may be transferred to reading in the less dominant language (e.g. Muljani et al, 1998; Wang et al, 2003). Moreover, some studies have shown that language proficiency may also have an effect on the extent to which each strategy may be employed (e.g. de Groot et al, 2002), but there has been little research on the issue of which factor may be more influential; orthographic transparency or language proficiency. Indeed, most recently it has been suggested that while language proficiency had relatively little effect on the type of strategy used by bilinguals, reliance on lexical or sublexical processing was largely constrained by the orthographies themselves (e.g. Meschyan & Hernandez, 2005; Simon et al, 2006).

The following experiment was aimed at examining the reading strategies employed by bilinguals of Spanish (L1) and English (L2), and Hebrew (L1) and English (L2), compared to English monolinguals, using a behavioural word / non-word naming task, measuring reaction time (RT) and accuracy. The rationale behind this type of experiment was that examining the differences between the three native languages would replicate the results observed by Frost and colleagues (1987), and the inclusion of bilinguals would allow for a controlled within-subject comparison between the two extremities of the continuum and English, as well as an examination of whether transfer of strategy may occur between L1 and L2, and if so, to what extent.

These comparisons would prove reliable if the between-language differences were to vary systematically, in keeping with their ‘position’ along the orthographic transparency continuum, while within-language trends in English were to be similarly manifested across the 3 groups.

As an optimal reflection of natural reading (e.g. Balota & Chumbley, 1984; de Groot et al, 2002), the naming task has been chosen for the behavioural aspect of the study, with naming latency and accuracy as the experimental measures. The variance observed in these measures, shaped by word-frequency, string-length and lexicality, have been previously shown to be reflective of the interplay between sublexical and lexical processing occurring during natural reading in monolinguals (e.g. Glushko, 1979; Henderson, 1982; Balota & Chumbley, 1985; Weeks, 1997; Rastle & Coltheart, 1998). The naming task has therefore been extensively used in conjunction with other types of tasks, in cross-language (Frost et al, 1987; Wydell & Butterworth, 1999; Wydell, Butterworth, & Patterson, 1995; Paulesu et al, 2000; Ziegler et al, 2001; de Groot et al, 2002) and within-language studies (e.g. Baluch & Besner, 1991; Wydell et al, 2003; Frost et al, 1994; 1995). These have pointed towards the notion that the type of processing involved in word recognition is largely shaped by the level of orthographic transparency of the writing system.

Bilinguals and monolinguals alike were therefore expected to show faster naming latency and higher accuracy levels for high-frequency words and for short words, relative to low-frequency words and long words, respectively, as well as faster naming latency for real words relative to non-words. Since the battery of stimuli was compiled using various databases (please refer to section 3.1.2.2: experimental stimuli and procedure), such finding would also confirm their adequacy for subsequent experiments. In addition, if reliance on lexical / semantic processing is the most efficient strategy for reading in Hebrew, then word-frequency and lexicality would have pronounced effects on naming latency in this language, relative to string-length. This pattern would be reversed in Spanish, where predominant sublexical assembly of phonology would lead to increased naming latency for long letter-strings, particularly for low-frequency words and non-words. Given that English is less transparent than Spanish, but more transparent than Hebrew, both bilingual groups as well as English monolinguals were expected to show naming latency patterns resembling those observed in Hebrew for real word trials, and those observed in Spanish for non-word trials.

Moreover, an assessment of the patterns of naming accuracy would further support the predicted reliance on different strategies for naming in the different languages (c.f. Wimmer & Hummer, 1990; Ellis & Hooper, 2001; Seymour & Elder, 1986; Stuart & Coltheart, 1988; Ellis et al, 2004). Specifically, in the transparent Spanish orthography, naming accuracy was expected to mirror the putative naming latency patterns. In English and Hebrew, high levels of accuracy was expected for high-frequency words, while the low level of exposure to low-frequency words was expected to give rise to a relatively high proportion of mispronunciations. Non-word accuracy was expected to be high in both languages, since in English non-words can be correctly pronounced using sublexical assembly, and in Hebrew, any assignation of spoken vowels would be considered as correct in a consonant string that has no meaning.

3.1.2 Method

3.1.2.1 Participants

Ninety participants[13] (47 female, 43 male), aged between 18 and 65 (mean age 32 years ±9) took part in the present experiment. These were recruited by word of mouth and were not paid for participation. All had normal or corrected-to-normal vision, received between 12 and 26 years of formal education (mean 18 years ±3), and had no history of learning disability or reading impairment.

Participants were divided into 3 groups, according to their respective native language; Spanish-English bilinguals, Hebrew-English bilinguals, and English monolinguals. Bilinguals were chosen on account of language proficiency, based on personal history and questionnaires (please refer to Appendix 1), and corroboration with data from behavioural experiment.

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[13] The original sample comprised 95 participants. The data of 4 participants were excluded from the analyses due to considerably low level of accuracy (more than 20 errors) and / or slow reaction time resulting in a high proportion of non-responses (more than 10). One participant was texting on their mobile phone between trials and therefore also excluded from the analysis

Bilinguals were considered as those individuals who could speak and read fluently in two languages, normally through formal education, residence in 2 countries and/or as a result of having spoken 2 languages at home. Spanish-English bilinguals (N=30; 14 female, 16 male) had been raised in a Spanish-speaking country (Chile, Argentina, Mexico, Spain, Bolivia and Venezuela), and Hebrew-English bilinguals (N=30; 18 female, 12 male) had been raised in Israel. All bilinguals had received English lessons in their native country since primary school. All were living in the UK for a minimum of 1 year at the time of testing, and were either enrolled in an English-speaking higher education programme, or were working in an English-speaking environment. English monolinguals (N=30; 15 female, 15 male), had been raised in the UK and were not proficient in any other language.

Table 3-1 shows bilingual and monolingual participants’ demographic details.

Table 3-1 *Bilingual and Monolingual participants' demographic details*

	Spanish-English bilinguals (N=30)		Hebrew-English bilinguals (N=30)		English monolinguals (N=30)	
	Range	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)
Age (years)	18-55	31.6 (7.7)	19-61	32.2 (9.1)	18-65	31.4 (10.5)
Formal education (years)						
Overall	13-26	19.1 (3.4)	12-22	16.7 (2.2)	14-24	18.1 (2.4)
Spanish	0-23	15.3 (5.6)	-	-	-	-
Hebrew	-	-	8-18	13.7 (2.7)	-	-
English	**0-13**	**4.5 (3.7)**	**0-9**	**2.6 (2.3)**	14-24	18.1 (2.4)
Age of acquisition (years)						
Spanish	Native		-	-	-	-
Hebrew	-	-	Native		-	-
English*	0-14	8.6 (3.9)	0-13	8.7 (2.9)	Native	
Length of residence (years)						
Spanish-speaking country	4-52	25.7 (8.4)	-	-	-	-
Israel (Hebrew speaking)	-	-	13-47	24.7 (9)	-	-
English-speaking country	1-20	6.1 (4.6)	1-36	6.1 (5.6)	Native	
Language exposure (hours per week)						
Spanish	0.5-90	30.8 (27)	-	-	-	-
Hebrew	-	-	1.5-90	37 (30.2)	-	-
English	5-90	74.4 (25.8)	3-90	68.8 (25.7)	>90	>90

Figures in bold indicate a statistically significant difference between the two bilingual groups, as revealed by a one-way ANOVA, $F_{(1,58)}$=4.04 p=0.05 (all other demographic factors did not differ significantly between the two groups [F's < 1.1 $p > 0.05$])

** note that 1 Spanish-English bilingual and 2 Hebrew-English bilinguals were raised by English-speaking parents, and considered themselves as native English speakers. For these participants English AoA was therefore annotated as zero*

3.1.2.2 Experimental stimuli and procedure

Experimental stimuli consisted of Hebrew, Spanish and English words and non-words (presented in Appendix 2). Words were selected according to frequency of occurrence, with high-frequency words occurring over 100 times per million and low frequency words occurring less than 10 times per million, from a number of available databases, as well as previous studies (Hebrew words: McCauly, in preparation; Frost, 1994; Spanish words: Almeida,1995[14]; English words: MRC Psycholinguistic database, 1987; Behrmann & Bub,1992). In order to avoid between-language priming effects, none of the chosen words shared semantic characteristics with the other languages. Non-word stimuli were created by replacing one or two single letters of real words, or selected from previous studies (English non-words: Behrmann & Bub, 1992; Spanish non-words Tamariz, 2003). All non-words were pronounceable, and followed the grammatical and orthographic rules of each language. The phonology of non-words in any given language did not represent real words in the other languages. The number of initial phonemes of all experimental trials was balanced in order to minimise possible effects of differential sensitivity of the voice-key to sound intensity and onset of naming.

Each language comprised one experimental block. Each block contained 90 trials; 60 words and 30 non-words. Word trials were divided into sub-blocks of 15 trials. These were high-frequency short words, high-frequency long words,

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[14] Note that since Spanish bilinguals were nationals of several different countries, care was taken to include only words which were universal to the Spanish-speaking population, for example, the word *ámbito* (field) features regularly in newspapers and is therefore considered as high-frequency, whereas the word *abad* (priest), in contrast to its popular synonym *sacerdote* appears relatively rarely in Spanish writings and is therefore considered as low-frequency.

low-frequency short words and low-frequency long words. Non-word trials were subdivided into 15 short and 15 long items. String-length was chosen in accordance with the optimal average of word length in each language (Kamps, Monz & Rijke, 2002). Short words and non-words therefore consisted of 3 letters for the Hebrew and English blocks, and 4 letters for the Spanish block. Consequently, long words consisted of 5 letters for the Hebrew and English blocks, and 6 letters for the Spanish block.

The experiment took place in a quiet room, at a place of the participants' convenience; usually their home or office. Experiments were conducted using a Pentium 4 Packard Bell laptop, connected to a voice-activated key and a microphone. The microphone was attached to a head-set such that it remained in a fixed position relative to participants' mouth. Stimuli were presented using SuperLab Pro 2.0.4 (Cedrus, 2003).

Bilingual participants were presented with stimuli in their native language and in English, while monolingual participants were presented with English stimuli only. The experiment lasted approximately 45 minutes. The session commenced with the calibration of the voice-key, followed by instructions and a short practice session of 18 word trials in each language. Once the instructions had been clearly understood and participants' comfort was ensured, the experiment began. Participants were instructed to read each word once, as quickly and as accurately as possible. It was highlighted that in the event of an unknown word appearing, participants should try to guess the correct pronunciation as quickly as possible. Prior to the onset of each language block an introductory sentence appeared at the centre of the screen, in the corresponding language, instructing participants to read aloud the words that were to follow. At the end of each language block, a smile sign appeared, followed by a concluding sentence indicating that the block had finished and the language was about to change. This was followed by a new introductory sentence indicating the language that was to follow. Participants were asked to read these introductory and concluding sentences silently.

Each stimulus appeared following a 500 ms fixation cross in the centre of the screen, and disappeared with the detection of onset of voice input. Naming latency was recorded by the computer, and accuracy of pronunciation by the experimenter. Stimuli were displayed for a maximum of 3000 ms. Where no response was detected during this time the programme proceeded to display the next trial. Words and non-words were presented in a randomised order, and the order of language block presentation was counterbalanced across the entire experimental group. Statistical analysis was performed using SPSS 13.0 for windows (SPSS Inc. 2000).

3.1.3 Results

Naming latencies for correct responses were averaged across participants for each language and each condition. Within each participant, response latencies in each condition falling outside the range of 2.5 standard deviations (SD) from the respective mean were discarded, and the mean was recalculated. Outliers accounted for less than 2% of all trials. Other discarded trials were those where the voice-key had been triggered by environmental noise or where participant response was not recorded due to voice-key insensitivity. These trials accounted for less than 4% of all trials.

Table 3-2 shows the mean reaction times in milliseconds and SD of correct responses, for each experimental condition for the three different languages, with Figures 3-1, 3-4 and 3-7 illustrating the effects and interactions between the different variables in each language, respectively. Note that for visual clarity error bars were omitted due to overlap in these multiple series figures. Table 3-3 and Figures 3-2, 3-5 and 3-8 show the error rate for each condition. As in Ellis et al’s study (2004) incorrect responses were categorised according to 4 different ‘types’. These are shown in Table 3-4 and Figures 3-3, 3-6 and 3-9. Table 3-5 shows the proportional differences in naming latency between different conditions within each language (ms and % effect). Regression analysis showed no effect of age, gender or level of formal education on overall naming latency. For interest, these are presented in Appendix 3.

Table 3-2 *Mean naming latency in milliseconds (ms), achieved by bilinguals and monolinguals in each language (figures in brackets represent SD.)*

	Spanish-English bilinguals		Hebrew-English bilinguals		English monolinguals
	Spanish	English	Hebrew	English	English
High-freq short words	716 (72)	734 (78)	709 (90)	729 (76)	660 (57)
High-freq long words	728 (75)	770 (96)	806 (93)	772 (90)	682 (72)
Low-freq short words	753 (80)	779 (94)	774 (90)	777 (109)	679 (55)
Low-freq long words	824 (102)	821 (100)	842 (106)	882 (160)	721 (66)
Overall word naming	755 (79)	776 (87)	783 (56)	790 (65)	685 (59)
Short non-words	844 (110)	815 (113)	1054 (281)	824 (160)	726 (78)
Long non-words	945 (154)	886 (140)	1072 (242)	982 (197)	816 (128)
Overall nw naming	894 (129)	850 (121)	1063 (13)	903 (111)	771 (97)

Table 3-3 *Incorrect responses [mean (SD)] made by bilinguals and monolinguals*

	Spanish-English bilinguals		Hebrew-English bilinguals		English monolinguals
	Spanish	English	Hebrew	English	English
Overall naming errors	3.17 (2.7)	4.87 (3.1)	1.27 (0.9)	4.57 (2.1)	1.2 (1.1)
High-freq short words	0	0	0	0	0
High-freq long words	0	0.1 (0.4)	0	0.17 (0.4)	0
Low-freq short words	0.03 (0.2)	0.57 (1)	0.33 (0.6)	0.47 (0.6)	0.07 (0.4)
Low-freq long words	0.33 (0.9)	2.93 (1.4)	0.43 (0.7)	2.67 (1.2)	0.6 (0.7)
Short non-words	0.73 (1)	0.87 (1.2)	0.3 (0.5)	0.37 (0.6)	0.17 (0.5)
Long non-words	2.07 (1.7)	0.4 (0.6)	0.2 (0.4)	0.9 (0.8)	0.37 (0.8)

Table 3-4 *Types of errors made by bilinguals and monolinguals [mean errors (SD)]*

	Spanish-English bilinguals		Hebrew-English bilinguals		English monolinguals
	Spanish	English	Hebrew	English	English
Stress Assignment	2.2 (2.0)	0.17 (0.5)	0.03 (0.2)	0.03 (0.2)	0
Phonological errors	0.47 (0.7)	4.1 (2.5)	0.77 (0.8)	3.0 (1.6)	0.93 (0.8)
Lexicalisation	0.2 (0.5)	0.53 (0.8)	0.17 (0.4)	0.6 (0.8)	0.17 (0.5)
Word Substitution	0.3 (0.8)	0.07 (0.2)	0.3 (0.2)	0.97 (1.1)	0.13 (0.4)

Types of errors were categorised as:

- *Stress assignment; referring to incorrect assignment of stress of polysyllabic words*
- *Phonological errors; referring to violation of correct phonemic pronunciation of words. In Spanish, these errors could be pronouncing a silent H. In English, these errors can be made predominantly in irregular words e.g. 'gauge', while in Hebrew these errors can be made by assigning an incorrect vowel to a consonant string, e.g. the string GMD (גמד), which should be pronounced as 'gamad' to mean dwarf, could be mistakenly pronounced 'gemed', which has no meaning*
- *Lexicalisation; pronouncing non-words as though they were real words, e.g. 'grink' as drink*
- *Word substitution; errors stemming from swapping the position of letters within words, such as 'beard' and 'bread'.*

Table 3-5 *Proportional differences in naming latency between different conditions within each language (ms and %)*

		Spanish-English bilinguals				Hebrew-English bilinguals				English monolinguals	
		Spanish		English		Hebrew		English		English	
		ms	%	ms	%	ms	%	ms	%	ms	%
Freq effects (low – high)	Short words	37	5	44	5	65	8	48	6	19	3
	Long words	96	11	50	6	36	4	110	11	39	5
	Overall	66	8	47	6	50	6	79	9	29	4
Length effects (long – short)	High-freq words	12	2	36	4	97	12	43	5	22	3
	Low-freq words	71	8	41	5	68	8	105	11	42	6
	Overall words	41	5	38	5	82	10	74	9	32	4
	Non-words	101	10	71	7	18	2	157	15	89	10
Lexicality effects (nw – words)	Short letter-strings	109	13	58	7	312	26	71	8	57	8
	Long letter-strings	168	17	90	10	248	21	154	14	114	13
	Overall	139	15	74	8	280	24	112	12	85	10

Statistical significance of naming patterns was assessed using repeated-measures analysis of variance (ANOVA), across subjects (F1) and across items (F2) separately. Data obtained in native languages was analysed within each group individually, and data obtained in English as a second language (ESL) was analysed between the two bilingual groups.

3.1.3.1 Naming in Spanish

3.1.3.1.1 Naming latency

Naming latency in Spanish increased systematically between high-frequency short words and long non-words. A 3x2 ANOVA, with “Frequency” (high-frequency words, low-frequency words and non-words) and “Length” (short words and long words) as within-subject factors, revealed significant main effects of frequency: $F1_{(2,58)}=126.99$, $p<0.0001$; $F2_{(2,28)}=48.38$, $p<0.0001$ and length: $F1_{(1,29)}=84.85$, $p<0.0001$; $F2_{(1,14)}=38.29$, $p<0.0001$, and a significant interaction between them: $F1_{(2,58)}=27.64$, $p<0.0001$; $F2_{(2,28)}=4.11$ $p<0.02$. Figure 3-1 illustrates very clearly the systematic increase in naming latency between high-and low-frequency words, particularly for long letter-strings, indicating a strong modulation of length effect by word frequency in Spanish. The overall lexicality effect in Spanish was 139 ms, with a 109 ms difference in naming latency between short words and short non-words, and a 168 ms difference between long words and long non-words. A 2x2 ANOVA, with “Lexicality” (real words and non-words) and “Length” (short and long letter-strings) with high- and low-frequency words averaged together, as within-subject factors, thus revealed main effects of lexicality: $F1_{(1,29)}=128.18$, $p<0.0001$; $F2_{(1,14)}=52.82$, $p< 0.0001$ and of length: $F1_{(1,29)}=75.96$, $p<0.0001$; $F2_{(1,14)}=43.09$, $p<0.0001$. The interaction between them was significant in the subject analysis: $F1_{(1,29)}=20.94$, $p<0.0001$, and approached significance in the item analysis ($F2_{(1,14)}=3.42$, $p=0.09$), suggesting that length effects were also modulated by lexicality in Spanish, i.e. the magnitude of length effects was stronger for non-words than for words.

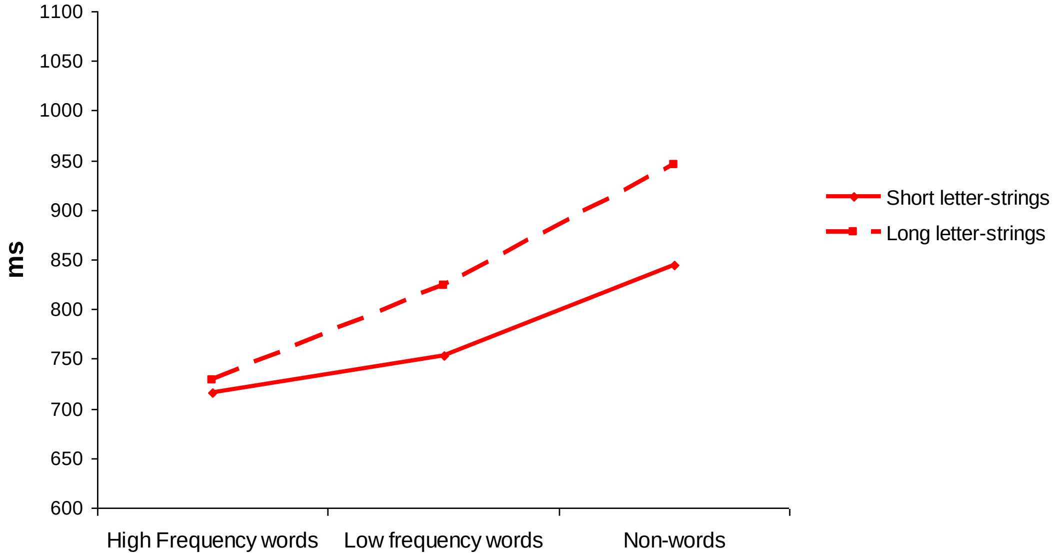

Figure 3-1 *Naming latency in Spanish*

3.1.3.1.2 Naming accuracy

Native Spanish bilinguals responded accurately on 96.5% of trials in their native language. Out of a mean of 3.17 (see Table 3-3), no errors were made while naming high-frequency words. Figure 3-2 clearly illustrates the naming accuracy pattern was similar to that of naming latency, whereby participants tended to make more errors while naming longer and less frequent words. A paired-samples Wilcoxon test on raw error scores revealed a significant frequency effect on naming accuracy for long words: z=-2.33, p<0.02, but not for short words (z=-1, p=0.32). Moreover, the length effect increased systematically as frequency decreased, with a nearly significant effect for low-frequency words (z=-1.90 p=0.06), and a strongly significant effect for non-words: z=-3.49, p<0.0001. Similarly, length effects on naming accuracy were modulated by lexicality, with a significant lexicality effect seen for short letter-strings: z=-3.37, p<0.001, and a stronger effect seen for long letter-stings: z=-4.39, p<0.0001.

As seen in Table 3-4 and Figure 3-3, incorrect stress assignment was the predominant type of error in Spanish (70%). Since error types were grouped into four categories, as in Ellis et al's study (2004) a Friedman's two-way analysis by ranks was used to measure the statistical significance of this observation. The analysis revealed that this type of error was significantly greater than the proportion of phonological errors (14%), lexicalisation (7%) and word substitutions (9%): $\chi^2_{(3)}$= 60.86, p<0.001.

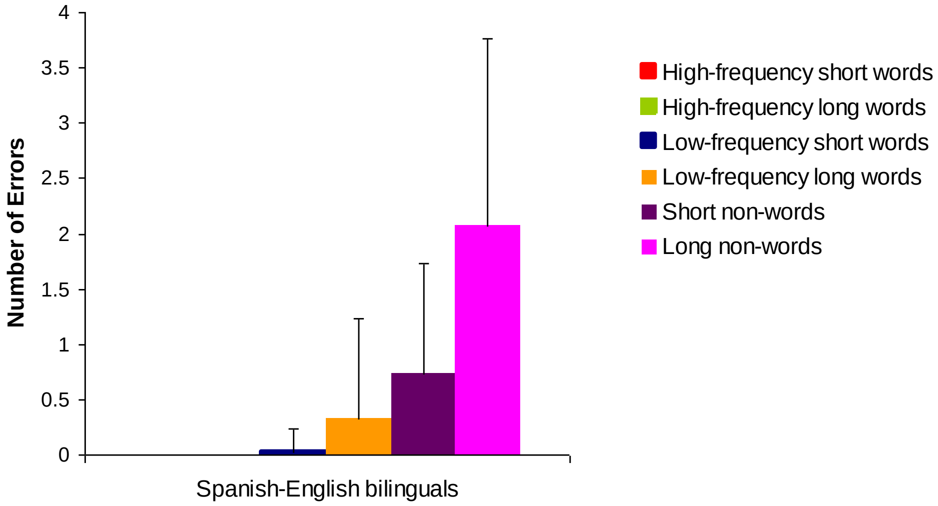

Figure 3-2 *Naming errors in Spanish*
Error bars represent SD from the mean as indicated in Table 3-3

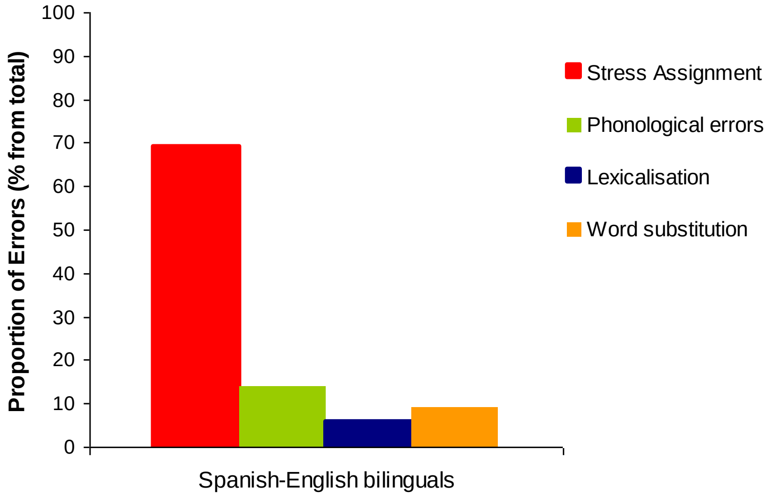

Figure 3-3 *Types of errors made in Spanish*

Correlation analysis, performed between accuracy levels and the demographic data obtained in the initial questionnaire in each language for each group, revealed that the overall Spanish accuracy rate was related to the proportional amount of time of formal education in Spanish: $r=0.42$, $p<0.02$, indicating that those participants who had spent more time studying in their native language relative to their second language tended to make less naming errors.

3.1.3.2 Naming in Hebrew

3.1.3.2.1 Naming latency

As shown in Table 3-2, high-frequency words in Hebrew were named faster than low-frequency words, short words were named faster than long words and short non-words were named faster than long non-words. 3x2 ANOVA therefore revealed significant main effects of frequency: $F1_{(2,58)}=59.68$, $p<0.0001$; $F2_{(2,28)}=98.96$, $p<0.0001$, and length: $F1_{(1,29)}=38.40$, $p<0.0001$; $F2_{(1,14)}=12.33$, $p<0.003$. However, the interaction between these factors, although significant across subjects: $F1_{(2,58)}=7.89$, $p<0.005$, did not reach significance across items ($F2_{(2,28)}=1.79$, $p=0.19$). More importantly, the interaction was in the opposite direction to that seen in Spanish. As clearly seen in Figure 3-4, the length effect in Hebrew systematically *decreased* as a function of frequency; for high-frequency words participants showed a 97 ms increase between short and long items, for low-frequency words this difference was 68 ms, and for non-words it was only 18 ms. It is important to note that short letter-strings in Hebrew are phonologically more ambiguous than long letter-strings, which are likely to carry partial phonetic information conveyed by mothers of reading, and allow some phonological recoding to take place when a lexical representation is not available.

In addition, the lexicality effect was considerably large in Hebrew (280 ms), particularly for *short* (312 ms) relative to long letter-strings (248 ms). The 2x2 ANOVA produced significant main effects of lexicality: $F1_{(1,29)}=59.73$, $p<0.0001$; $F2_{(1,14)}=111.77$ $p<0.0001$ and length: $F1_{(1,29)}=15.01$, $p<0.001$; $F2_{(1,14)}=5.78$, $p<0.03$, and an interaction, which was inversely related to string-length, and statistically significant across subjects: $F1_{(1,29)}=7.87$, $p<0.009$, but not across items ($F2_{(1,14)}=2.79$, $p=0.12$).

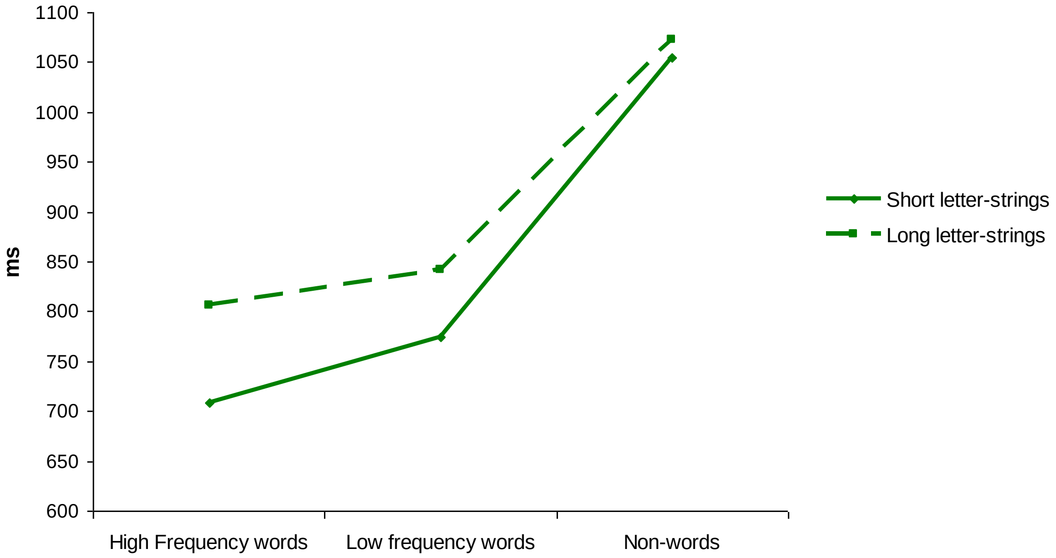

Figure 3-4 *Naming latency in Hebrew*

3.1.3.2.2 Naming accuracy

Native Hebrew bilinguals achieved an accuracy level of 98.6%. The largest proportion of errors in Hebrew was related to phonological mispronunciations (Fig 3-6): $\chi^2_{(3)}= 39.31$, $p<0.001$, made mostly during low-frequency word naming, with no errors for high-frequency words, and a very small proportion of errors made while naming non-words (Fig 3-5)[15]. Correlation analysis revealed that the overall accuracy rate in Hebrew was strongly related to the total number of years of formal education: $r=0.54$, $p<0.002$, suggesting that those participants who had a higher level of education tended to make fewer errors in Hebrew. In keeping with this observation, considerably strong effects of word-frequency were observed for short and long words: $z=-2.64$, $p<0.008$ and $z=-2.92$, $p<0.004$, respectively, though no significant effects of string-

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[15] Note that the criteria for assessing an error in the three languages are shaped by their orthographic properties. This is particularly important for Hebrew non-words, where any pronunciation that is consistent with the consonant string may be regarded as correct, since the lack of written vowels allows a high level of flexibility in non-word naming.

length or lexicality were observed for naming accuracy (all z values > -1.40 and all p values > 0.16).

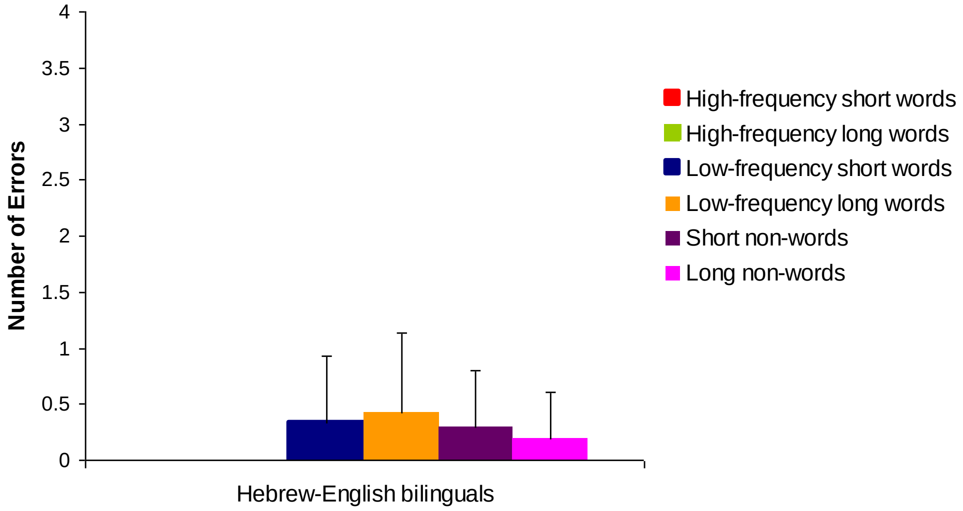


Figure 3-5 *Naming errors in Hebrew*
Error bars indicate SD from the mean as indicated in Table 3-3

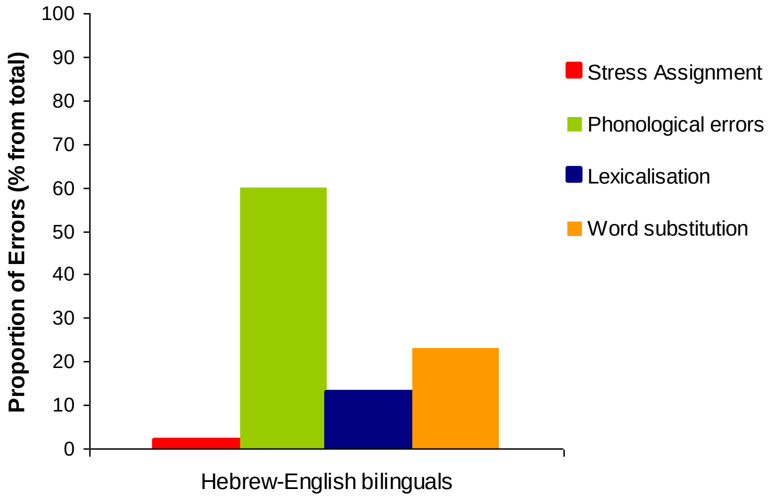


Figure 3-6 *Types of errors made in Hebrew*

3.1.3.3 Naming in English

3.1.3.3.1 Naming latency

Native English speakers, having performed the test in one language only, exhibited overall considerably faster naming relative to their bilingual counterparts. The latency patterns, however, were similar to those seen previously, with high-frequency words being named faster than low-frequency words, short letter-strings being named faster than long letter-strings, and real words being named faster than non-words. Concordantly, the 3x2 ANOVA revealed significant main effects of frequency: $F1_{(2,58)}=53.13$, $p<0.0001$; $F2_{(2,28)}=31.40$, $p<0.0001$, and length: $F1_{(1,29)}=53.23$, $p<0.0001$; $F2_{(1,14)}=24.32$, $p<0.0001$, and a significant interaction between them: $F1_{(2,58)}=13.04$, $p<0.0001$; $F2_{(2,28)}=3.97$, $p<0.03$. The 2x2 ANOVA revealed significant main effects of lexicality: $F1_{(1,29)}=55.75$, $p<0.0001$; $F2_{(1,14)}=46.44$, $p<0.0001$, and length: $F1_{(1,29)}=46.79$, $p<0.0001$; $F2_{(1,14)}=26.03$, $p<0.0001$, and a significant interaction between them: $F1_{(1,29)}=14.08$, $p<0.001$; $F2_{(1,14)}=6.82$, $p<0.02$.

These observations suggest that similar to Spanish, length effects were modulated by frequency and lexicality in English, though as seen in Figure 3-7, this modulation was not as strong as in Spanish.

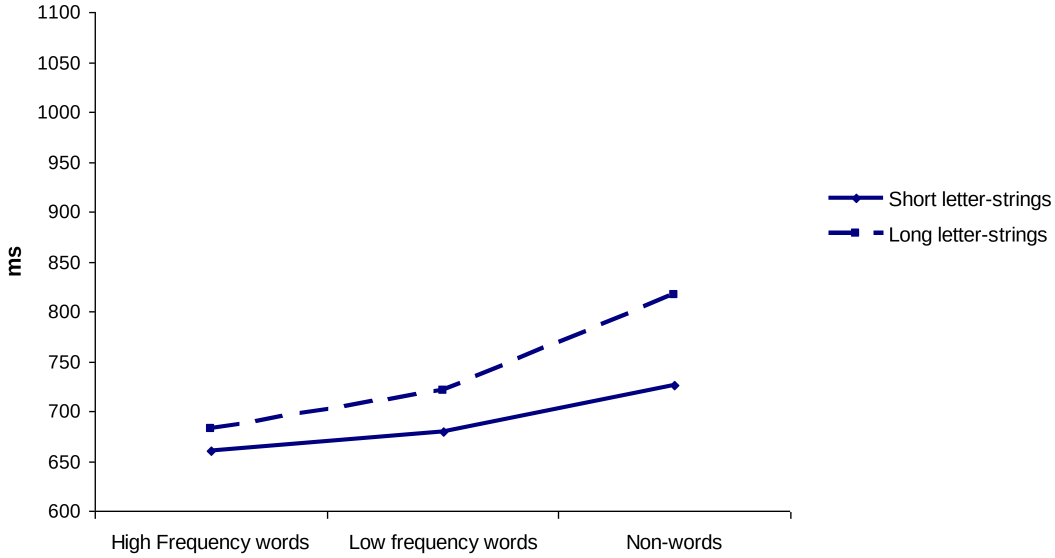


Figure 3-7 *Naming latency in English*

3.1.3.3.2 Naming accuracy

Accuracy level in English was a high 98.7%. As observed in the two bilingual groups, no naming errors were made in high frequency-word trials (Table 3-3, Fig. 3-8). The majority of errors were phonological mispronunciations (Fig.3-9): $\chi^2_{(3)}=70.05$, $p<0.001$, made predominantly while naming long low-frequency long words. Concordantly, the difference between long and short low-frequency words was significant: $z=-3.63$, $p<0.0001$. As observed in Hebrew, less errors were made in non-words relative to low-frequency words, though the difference did not reach statistical significance (all z values > -1.67, all p values >0.09). In this group of participants there was no indication that lexicality significantly modulated the effect of string-length on naming accuracy, despite the fact that more errors were made while naming long, relative to short non-words. In addition, no correlations were observed between accuracy level and any demographic data in this group of participants.

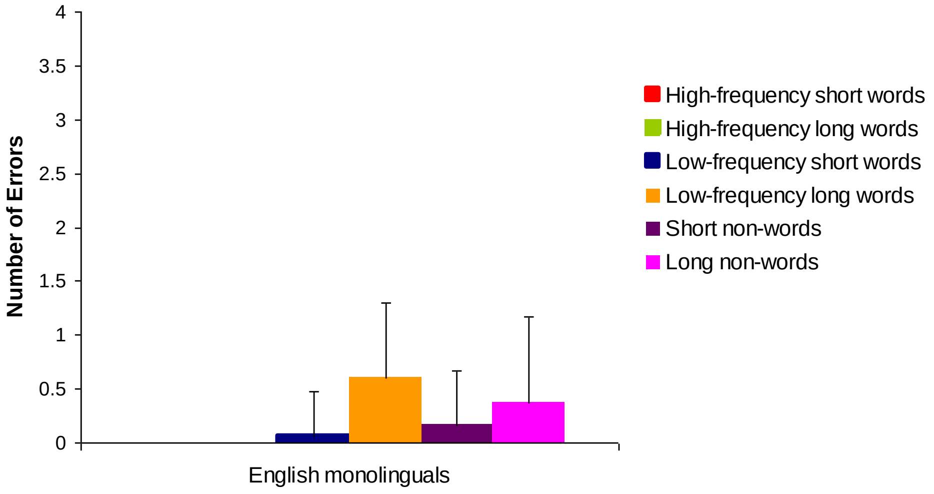


Figure 3-8 *Naming errors in English*
Error bars indicate SD from the mean as indicated in Table 3-3

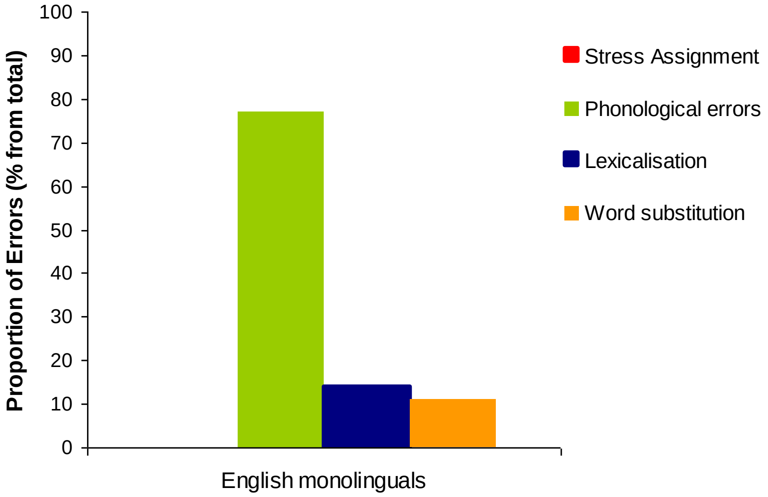


Figure 3-9 *Types of errors made in English*

3.1.3.4 Naming in English as a second language (ESL)

3.1.3.4.1 Naming latency

Naming words in ESL was somewhat slower than in the native languages, though naming non-words was somewhat faster. For the *native Hebrew speakers*, the within-subject / between-language ANOVA revealed significant main effects of language: $F1_{(1,29)}=5.82$, $p<0.02$; $F2_{(1,14)}=17.54$, $p<0.001$ in the frequency and length effects analysis and $F1_{(1,29)}=10.07$, $p<0.004$; $F2_{(1,14)}=27.83$, $p<0.0001$, for the lexicality and length effects analysis, suggesting that naming latency of words was significantly faster in Hebrew than in English, while naming non-words was significantly faster in English than in Hebrew. For the *native Spanish speakers* the trends were similar, thought did not reach statistical significance ($F1_{(1,29)}=0.002$, $p=0.97$; $F2_{(1,14)}=0.006$, $p=0.94$ for the frequency and length effects analysis, and $F1_{(1,29)}=0.51$, $p=0.46$; $F2_{(1,14)}=1.37$, $p=0.26$ for the lexicality and length effects analysis).

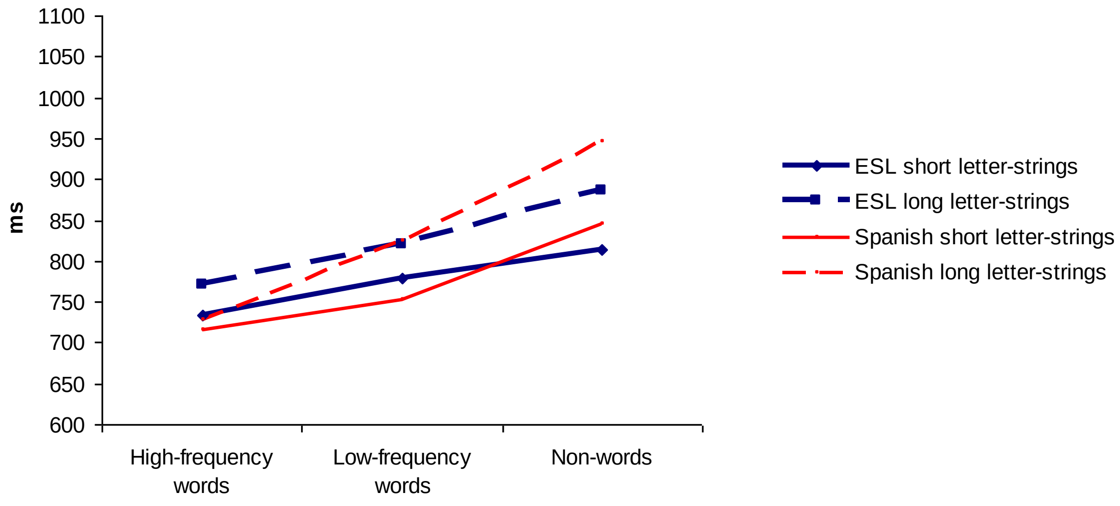
Both bilingual groups showed a similar pattern of effects and interactions in ESL to that observed in the native English counterparts, whereby high-frequency words were named faster than low frequency words, short letter-strings were named faster than long letter-strings and real words were named faster than non-words. The between-subject / within-language 3x2 ANOVA revealed significant main effects of frequency: $F1_{(2,116)}= 118.73$, $p<0.0001$; $F2_{(2,56)}=49.25$, $p<0.0001$, and length: $F1_{(1,58)}=109.81$, $p<0.0001$; $F2_{(1,28)}=53.33$, $p<0.0001$, and a significant interaction between them: $F1_{(2,116)}=20.21$, $p<0.0001$; $F2_{(2,56)}=4.88$, $p<0.001$, suggesting that length effects in ESL were modulated by word frequency. The main effect of group did not reach statistical significance ($F1_{(1,58)}$=0.96, p=0.33, $F2_{(1,28)}$=3.44, p=0.07), suggesting that overall, both bilingual groups exhibited a similar naming pattern in ESL.

From Fig. 3-10, however, it is clear that group differences emerged in naming long letter-strings. Specifically, the native Hebrew speakers (Fig.3-10b) showed a considerable increase in latency when naming long low-frequency words and long non-words, compared to the native Spanish speakers (Fig. 3-10a). In keeping with this observation, the interaction between group and frequency was significant across subjects: $F1_{(2,116)}$=5.61, p<0.01, though not across items ($F2_{(2,56)}$=2.01, p=1.43), and the interaction between group and length was strongly significant across both: $F1_{(1,58)}$=13.09, p<0.001; $F2_{(1,28)}$=5.21, p<0.03. Similarly, the 3-way interaction was significant across subjects: $F1_{(2,116)}$=5.95 p<0.004, but did not reach significance across items ($F2_{(2,56)}$=1.23, p=0.30).

The 2x2 ANOVA revealed significant main effects of lexicality: $F1_{(1,58)}$=138.25, p<0.0001; $F2_{(1,14)}$=59.39, p<0.0001, and length: $F1_{(1,58)}$=102.97, p<0.0001; $F2_{(1,28)}$=45.78, p<0.0001, and a significant interaction between them: $F1_{(1,58)}$=30.72, p<0.0001; $F2_{(1,28)}$=6.28, p=0.02. The main effect of group was not significant across subjects ($F1_{(1,58)}$=1.30, p=0.26) though it approached significance across items: ($F2_{(1,28)}$=4.22, p=0.06). However, the interaction between group and lexicality was significant in the subject analysis: $F1_{(1,58)}$=5.79, p<0.02, but not in the item analysis ($F2_{(1,28)}$=2.16, p=0.15), and the interaction between group and length was significant in both:

$F1_{(1,58)}$=13.05, p<0.001; $F2_{(1,28)}$=4.69, p<0.04. This was due to the presence of an interaction between lexicality and length in the native Hebrew group, but not in the native Spanish group Fig 3-10). In keeping with these observations, the 3-way interaction was significant across subjects: $F1_{(1,58)}$=5.97, p<0.02, but not significant across items ($F2_{(1,28)}$=0.92, p=0.25).

a. Spanish-English bilinguals



b. Hebrew-English bilinguals

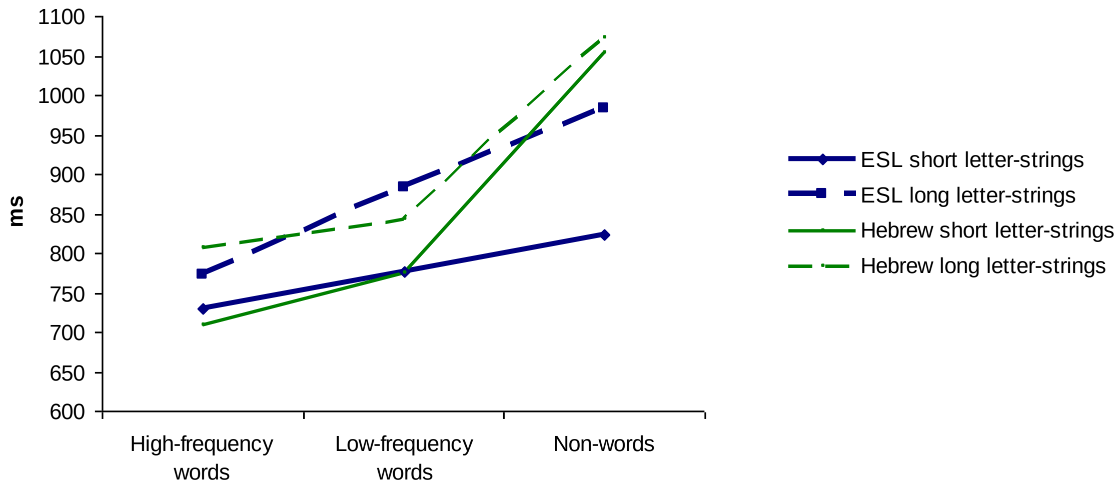


Figure 3-10 *Naming latency in English as a second language by bilingual participants;* ***a.*** *Spanish-English bilinguals;* ***b.*** *Hebrew-English bilinguals*

The between-group comparison of the proportional frequency, length and lexicality effects (independent samples t-test) showed that all effects were significantly stronger for the native Hebrew speakers relative to the native Spanish speakers: frequency effect: $t_{(58)}=-2.13$, $p<0.01$, word length effect: $t_{(58)}=-3.12$, $p<0.003$, non-word length effect: $t_{(58)}=-3.36$, $p<0.001$, and lexicality effect: $t_{(58)}=-2.36$, $p<0.02$. Table 3-5 clearly shows that this was predominantly true for low-frequency words and long letter-strings.

3.1.3.4.2 Naming accuracy

Both Spanish and Hebrew bilinguals exhibited a similar overall lower level of accuracy in ESL relative to their native languages. With accuracy levels of 94.6% and 94.9%, respectively, a within-group comparison revealed that ESL accuracy in both groups (see Fig. 3-11) was significantly lower than in the respective native languages: $z=-2.37$, $p<0.02$ for *Spanish bilinguals* and $z=-4.56$, $p<0.0001$ for *Hebrew bilinguals*. Equally, a between-group comparison revealed that both bilingual groups' ESL accuracy level was significantly lower than that of English monolinguals: $z=-5.2$, $p<0.0001$, for *Spanish bilinguals* and $z=-5.8$, $p<0.0001$ for *Hebrew bilinguals*, though clearly, no significant differences were seen between the two groups ($z=-0.28$, $p=0.78$).

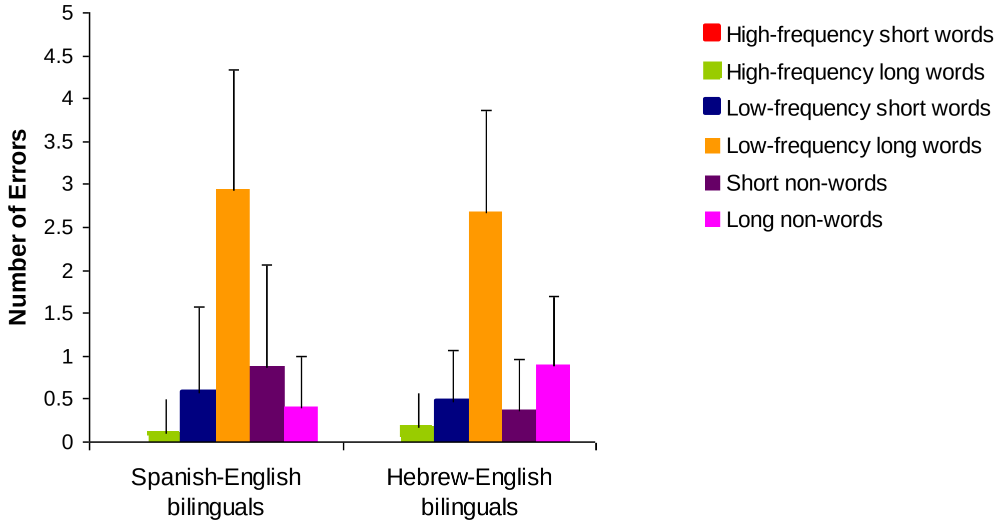


Figure 3-11 *Naming errors in English as a second language*
Error bars indicate SD from the mean as indicated in Table 3-3

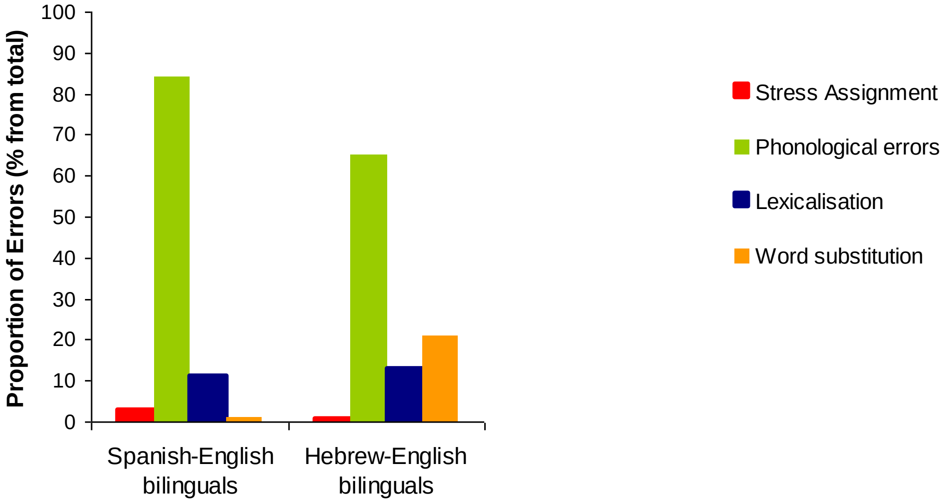


Figure 3-12 *Types of errors in English as a second language*

Both Spanish and Hebrew bilinguals showed a systematic increase in the mean number of errors made in word naming, from 0 errors for high-frequency short words to 2.93 and 2.67, respectively, for low-frequency long words (Table 3-3), and similar to their monolingual counterparts, the majority of errors were phonological mispronunciations: $\chi^2_{(3)}$=67.85, p<0.001 for the

Spanish bilinguals; $\chi^2_{(3)}$=58.92, p<0.001 for the Hebrew bilinguals, made predominantly in low-frequency long words. Interestingly, the Hebrew bilinguals showed a relatively large proportion of word substitution in ESL (a mean of 0.97, constituting 21% of overall number of errors), though this was not statistically significant ($\chi^2_{(3)}$=1.20, p=0.27). As seen in Table 3-6, frequency effects on naming accuracy in ESL were strong for both bilingual groups, and length effects were moderate for high-frequency words but strong for low-frequency words, suggesting an interaction between frequency and length effects on naming accuracy. For non-word trials both groups made a similar number of errors, though the pattern was somewhat different, whereby *Spanish bilinguals* made more errors in naming short non-words than long non-words, and *Hebrew bilinguals* showed the opposite pattern. Table 3-6 shows a marginal length effect on non-word naming accuracy for *Spanish bilinguals*, despite the strong lexicality effects, while for *Hebrew bilinguals*, a strong length effect on non-word naming accuracy emerged since the lexicality effect was only significant for long letter-strings.

Table 3-6 *Statistical values for effects of word frequency, string length and lexicality on naming accuracy in ESL – within-group comparison – related samples Wilcoxon signed ranks test*

	Spanish-English bilinguals	Hebrew-English bilinguals
Frequency effect on short word accuracy	***z=-2.87*** ***p<0.004***	***z=-3.5*** ***p<0.0001***
Frequency effect on long word accuracy	***z=-4.68*** ***p<0.0001***	***z=-4.74*** ***p<0.0001***
Length effect on High-frequency word accuracy	z=-1.34 p=0.18	***z=-2.23*** ***p<0.02***
Length effect on low-frequency word accuracy	***z=-4.49*** ***p<0.0001***	***z=-4.5*** ***p<0.0001***
Length effect on non-word accuracy	*z=-1.95* *p=0.05*	***z=-2.65*** ***p<0.008***
Lexicality effect on short letter-string accuracy	***z=-3.03*** ***p<0.002***	z=-0.87 p=0.38
Lexicality effect on Long letter-string accuracy	***z=-2.27*** ***p<0.0001***	***z=-2.71*** ***p<0.007***

Figures in bold highlight statistical significance

Correlation analysis showed that for the *native Spanish bilinguals* ESL naming accuracy was related to the age of acquisition of English: $r=-0.4$, $p<0.02$, suggesting that those participants who had started learning English at a younger age tended to achieve a higher accuracy level in the experiment. Similarly, for both groups ESL accuracy was related to the number of years of formal education in English: $r=0.4$, $p<0.03$ for *Spanish bilinguals* and $r=0.5$, $p<0.01$ for *Hebrew bilinguals*, suggesting that higher levels of exposure to English may have contributed to higher levels of accuracy achieved by bilingual participants.

3.1.4 Discussion

The present experiment was aimed at examining the different reading strategies employed by readers of 3 different languages, whose levels of orthographic transparency are considered to be placed along a continuum; from Spanish at the most transparent end, to Hebrew at the most opaque end, and English as the midpoint (c.f. Frost Katz and Bentin, 1987).

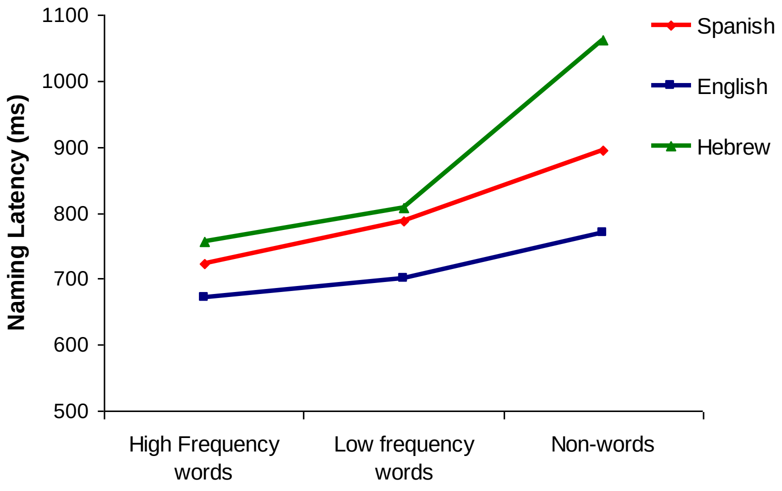
Bilinguals of Hebrew and English, and of Spanish and English were the chosen experimental sample, with English monolinguals as ‘controls’, providing a point of comparison for the common language to all participants.

Participants performed a behavioural word / non-word naming task, with naming latency and accuracy as the experimental measures. Results showed a consistent pattern for all participants, whereby high-frequency words were named faster than low-frequency words, short words were named faster than long words, and real words were named faster than non-words, thus confirming the adequacy of the experimental materials chosen for this and subsequent experiments. In addition, bilingual participants showed faster naming and higher accuracy in the respective native languages (with the exception of naming latency for non-words), as previously observed in multilingual studies (e.g. Chee et al, 2000; Hernandez et al, 2001; Jared & Kroll, 2001; de Groot et al, 2002; Vingerhoets et al, 2003; Meschyan & Hernandez, 2005; Simon et al, 2006). Concurrently, interesting between-language differences were observed in the patterns of naming latency and accuracy.

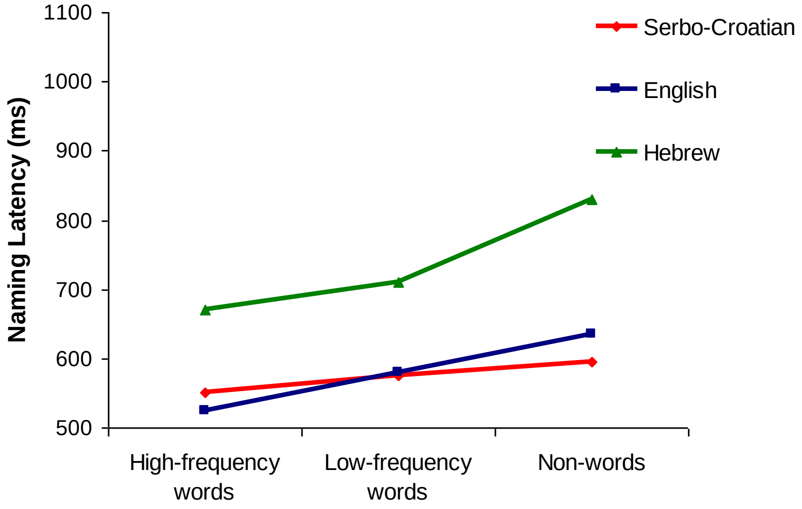
First, the interactions observed in the effects of frequency, length and lexicality on naming latency were varied. In Spanish, naming latency increased systematically as a function of word frequency, an effect which was strongly modulated by string length, i.e. naming low-frequency words and non-words was slower than naming high-frequency words, significantly more so for long letter-strings than for short ones. This type of pattern is suggestive of heavy reliance upon sublexical assembly of phonology for the correct pronunciation of low-frequency words and non-words (Balota & Chumbley, 1984; Jescheniak & Levelt, 1984). Concurrently, the strong frequency and lexicality effects were in accordance with previous studies showing that lexical access is essential for efficient reading even in transparent languages (Baluch & Besner, 1991; Ruiz, Ansaldo & Lecours, 1994; Paulesu et al, 2000; Rantavalli et al 2000; Iribarren et al, 2001; Karanth, 2002; Paulesu, 2006).

In English as a native language, a similar pattern was seen, with a somewhat weaker effect of string-length on the increase in naming latency for less frequent words, suggesting that naming in the language located in the ‘middle’ of the continuum was mediated by lexical / semantic processing to a greater extent than in Spanish, while phonological assembly of sound from print was also evident to some extent (Feldman, 1980; Lukatela et al, 1980; Feldman & Turvey, 1983; Frost et al, 1987; Weekes, 1997).

In contrast, the trend observed in Hebrew was reversed, with a *decrease* in the magnitude of frequency and lexicality effects, as a function of string-length. This inverse interaction was suggestive of predominant reliance on lexical knowledge for naming frequent as well as less frequent words. These findings are in-keeping with the weak version of the Orthographic Depth Hypothesis (Katz & Frost, 1992), predicting that in languages of shallow orthography the principal reading strategy is the sublexical assembly of phonology from print, while in languages of deeper orthographies the most efficient strategy is direct lexical retrieval. This notion was strengthened by the patterns observed in non-word naming, where logically, the most efficient strategy should be sublexical / phonological recoding due to the lack of lexical representation (Frost et al, 1987; Baluch & Besner, 1991, Tabossi & Laghi, 1992; Wydell et al, 2003). As expected, lexicality effects in Hebrew were markedly stronger than in Spanish and English, since lexical retrieval of nonexistent words is inefficient, and the absence of vowels in Hebrew renders the assembly of phonology virtually impossible. Moreover, when length effects were averaged out by averaging short and long letter-strings together, naming latency patterns from the present experiment replicated those of Frost et al’s (1987) Naming Experiment 1 (Figure 3-13).



a. Naming latency of bilinguals; short and long letter-strings averaged together



b. Naming latency of monolinguals as described in Frost et al's (1987) Experiment 1

Figure 3-13 a. *Naming latency of bilinguals; short and long letter-strings averaged together.* ***b.*** *Naming latency of monolinguals as described in Frost et al's (1987) Experiment 1*

Second, naming accuracy in all 3 native languages was 100% in high-frequency words, and systematically decreased as a function of word-frequency, particularly for long words. In Spanish this trend extended to non-words, parallel to the naming latency data, showing a significant modulation of frequency and lexicality effects by string-length on naming accuracy. In contrast, the greatest proportion of errors in English and Hebrew were made in low-frequency long words. The latter finding is not surprising, since in both languages, reliance on lexical knowledge should give rise to more errors in less frequent words.

In addition, the low error rate in non-words stemmed from the fact that in Hebrew, as noted earlier, there is no particular correct way to pronounce non-words, and in English, the phonology of non-words can be correctly assembled with the use of vowels. This of course had a cost, reflected in slower RTs.

In Spanish, however, the large proportion of errors in non-words may seem initially counterintuitive, though considering that the majority of errors were related to incorrect stress assignment of polysyllabic letter-strings, it is to be expected, since stress assignment is one of the few aspects of the Spanish orthography which requires implementing a set of rules, or lexical knowledge, in order to achieve correct pronunciation. Indeed, correlation analysis revealed that accuracy level was related to formal education, suggesting that more practised participants tended to have more knowledge of stress assignment rules. The present findings are also similar to those observed by Frost et al (1987), who found that in the shallow Serbo-Croatian, participants tended to make more lexical decision errors in non-words, whereas in English and Hebrew most errors were made in low-frequency words. Concordantly, errors in English and Hebrew were related predominantly to incorrect phonetic pronunciation. In addition, naming in Hebrew was associated with a relatively high proportion of lexicalisation errors i.e. wrongly perceiving a non-word as a word, and as in the native Spanish speakers, accuracy was related to participants' level of education.

Overall, the types of errors made in each language provide further support for the differential degrees of involvement of sublexical and lexical processing in each language, and show that the predominant reading strategies can be placed along the continuum in parallel to the level of orthographic transparency of each language.

One intriguing observation, which deserved further investigation, was the surprisingly strong length effect in Hebrew high-frequency words (97 ms). If the predominant strategy for reading in an orthographically opaque language such as Hebrew is direct lexical retrieval, then word-length, particularly at high-frequency should not affect naming latency. In order to continue interpreting the results of the bilingual naming experiment, it was necessary to ascertain whether this effect was 'real' i.e. originated as a result of slower perceptual analysis of longer high-frequency words in Hebrew, or whether some other unidentified factor had influenced this result. This led to the following delayed naming experiment in Hebrew.

3.2 Experiment 2: Delayed naming in Hebrew

3.2.1 Introduction

In order to clarify the issue of the counter-intuitive strong length effect seen in Hebrew high-frequency words, a delayed naming experiment was carried out with native Hebrew speakers only. Unlike standard naming, in a delayed naming task participants are instructed to name the word appearing on screen at the onset of a cue, presented some hundred milliseconds after initial stimulus presentation. Reaction time is measured from the onset of the cue rather than the stimulus. Since lexical access is believed to be completed within about 300 ms from stimulus presentation (Gough & Cosky, 1977; Rayner, 1978; McRae et al, 1990), the inclusion of a delay of 400 ms or more, should allow the participant to fully prepare a phonological output of the printed stimulus before responding. In keeping with this logic, the delayed naming task has been previously shown to significantly reduce overall naming latency (Balota & Chumbley, 1985; Monsell, Doyle & Haggard, 1989), diminish the magnitude of frequency effects (Mc Rae et al, 1999; de Groot et al, 2002) and in some cases cancel out length effects (e.g. Weekes, 1997; Zoccolotti et al, 2006).

In the present experiment, the delay was set at 600 ms, following the paradigm used by de Groot et al (2002), examining task effects on visual word recognition in bilinguals. It was expected that the inclusion of a delay would lead to a reduction in the exaggerated length effect seen between high- and low-frequency words in Hebrew, providing that it had emerged as a result of slower perceptual analysis of long high-frequency words, and not a confounding methodological variable.

3.2.2 Method

3.2.2.1 Participants

Twenty five native Hebrew speakers (14 female, 11 male), aged between 18 and 46 years (mean age 30.7 years ± 7.9) participated in the delayed naming experiment. All had received between 12 and 23 years of formal education (mean 16.6 years ± 3), and had no history of learning disability or reading impairment.

3.2.2.2 Experimental procedure

The delayed naming experiment was conducted using the laptop and voice-activated key as described in section 3.1.1.2 above.

The experiment lasted for approximately 30 minutes, and began with voice-key calibration, followed by verbal instructions, and a practice session of 10 word trials. The main experimental session consisted of the same 90 words and non-words used in the bilingual experiment, presented at the centre of the screen following a 500 ms fixation cross. Each stimulus appeared for 600 ms, followed by a question mark, coupled by an auditory cue. Participants were instructed to respond upon the appearance of the cue, by saying aloud the word they had seen, pronouncing it as quickly and as accurately as possible.

3.2.3 Results

Trials exceeding the threshold of 2.5 standard deviations above the mean of each subject and each condition were discarded and the mean was recalculated. These trials accounted for 1.9 % of all trials. In addition, where the microphone was triggered by an outside noise, participant had stuttered, made no response, or made an error, the mean was recalculated. Discarded trials accounted for 3% of all trials. As expected from a delayed naming task, overall latencies were reduced significantly relative to standard naming, as seen in Table 3-7. Concordantly, the effects of frequency, word-length and lexicality were weaker, as seen in Table 3-8.

Accuracy was considerably higher in the present experiment, with 14 participants responding correctly on all trials, 9 participants making 1 error, 1 participant making 2, and 1 participant making 3 errors. Accuracy data is therefore not included in the analysis.

Table 3-7: *Delayed and standard naming in Hebrew; Mean naming latency in milliseconds (ms), achieved by native Hebrew speakers [mean (SD)]*

	Delayed naming	Standard naming
High-frequency short words	332 (92)	709 (90)
High-frequency long words	355 (104)	806 (93)
Low-frequency short words	343 (98)	774 (90)
Low-frequency long words	369 (98)	842 (106)
Overall word naming latency	348 (93)	783 (56)
Short non-words	390 (106)	1054 (281)
Long non-words	405 (112)	1072 (242)
Overall non-word naming latency	398 (107)	1063 (13)

Table 3-8: *Delayed and standard naming in Hebrew; Proportional differences in naming latency between different conditions (ms and %)*

		Delayed naming		Standard naming	
		ms	%	ms	%
Frequency effects	Short words	11	2	65	8
	Long words	14	5	36	4
	Overall	12.5	3.5	50	6
Length effects	High-frequency words	23	5	97	12
	Low-frequency words	26	7	68	8
	Overall words	24.5	6	82	10
	Non-words	15	3	18	2
Lexicality effects	Short letter-strings	53	13	312	26
	Long letter-strings	42	10	248	21
	Overall	47.5	12.5	280	24

Repeated measures ANOVA on the delayed naming data revealed significant main effects of frequency: $F1_{(2,48)}=20.19$, $p<0.0001$; $F2_{(2,28)}=18.99$, $p<0.0001$ and length: $F1_{(1,24)}=12.7$, $p=0.002$; $F2_{(1,14)}=12.12$, $p<0.004$, but no interaction between them ($F1_{(2,48)}=0.74$, $p=0.48$; $F2_{(1,14)}=0.43$, $p=0.66$), suggesting that high frequency words were named significantly faster than low frequency words and short words were named significantly faster than long words, despite the 600 ms delay. However, the lack of interaction between frequency and length suggests that in this experiment the effect of length was not modulated by word frequency.

Similarly, the main effect of lexicality was significant: $F1_{(1,24)}=28.46$, $p<0.0001$; $F2_{(1,14)}=27.76$, $p<0.0001$, as was the main effect of length: $F1_{(1,24)}=11.77$, $p=0.002$; $F2_{(1,14)}=7.54$, $p<0.02$, but the interaction did not reach statistical significance ($F1_{(1,24)}=0.66$, $p=0.42$; $F2_{(1,14)}=0.58$, $p=0.46$). Therefore, real words were named significantly faster than non-words, and short letter-strings were named significantly faster than long-letter strings, but unlike in standard naming, string-length did not modulate lexicality effects in the delayed naming experiment.

Table 3-9 presents the statistical values of a 1-way ANOVA conducted in order to compare the magnitude of effects between standard and delayed naming. As seen in the table, the frequency effect for short words was significantly reduced with the delay, whereas that of long words was not. Importantly, the very strong 97 ms length effect in high-frequency words was reduced to 23 ms by the inclusion of a delay, as seen in Table 3-8. This difference was statistically significant, while the difference in length effect for low-frequency words was not, as illustrated in Table 3-9.

Table 3-9: *1-way ANOVA on the differences in magnitude of frequency, length and lexicality effects between standard and delayed naming task in Hebrew*

		$F_{(1,54)}$	p
% Frequency effects	Short words	***7.91***	***0.007***
	Long words	0.05	0.82
	Overall	2.45	0.12
% Length effects	High-frequency words	***9.64***	***0.003***
	Low-frequency words	0.24	0.63
	Overall words	3.83	0.06
	Non-words	0.23	0.63
% Lexicality effects	Short letter-strings	***20.18***	***<0.001***
	Long letter-strings	***12.26***	***0.001***
	Overall	***18.69***	***<0.001***

Figures in bold highlight statistical significance

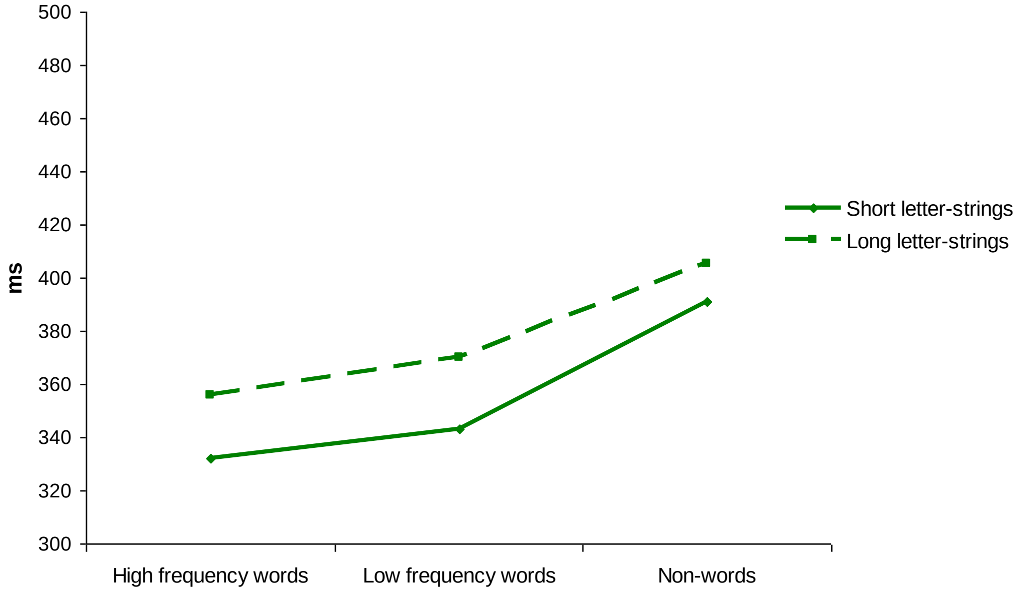


***Figure 3-14** Delayed naming latency in Hebrew*

3.2.4 Discussion

The delayed naming experiment was conducted in order to ascertain whether the unusually strong length effect seen in standard naming of Hebrew high-frequency words could have arisen as a result of an artefact. The logic of this type of experiment assumes that instructing subjects to respond to a cue, appearing some hundred milliseconds following a written stimulus allows lexical access to take place during the delay, and prepare a phonological output prior to the response (e.g. Balota and Chumbley, 1985; Weekes, 1997; Mc Rae et al, 1999), resulting in significantly smaller naming latencies compared to standard naming.

In the present experiment, the delay was set at 600 ms, following the paradigm used by de Groot et al (2002), who examined the factors influencing visual word recognition in bilinguals. It was felt that using a longer delay might eliminate the effects of frequency and length altogether, as seen in the studies conducted by McRae et al (1990), Weekes (1997) and Zoccolotti et al (2006), which in this context, would render the results uninformative.

Indeed, significant effects of frequency, length and lexicality still materialised at a delay of 600 ms, as observed previously (Balota & Chumbley, 1985; Monsell, Doyle & Haggard, 1989; McRae et al, 1990; de Groot et al, 2002). However, unlike the standard naming task in Experiment 1, the interactions between the variables were abolished. Importantly, the unexpected length effect in high-frequency words was greatly reduced by the inclusion of this delay, and was no longer larger than the effect for low-frequency words. It is therefore reasonable to conclude that the considerable difference in naming latency between short and long high-frequency words in Hebrew was due to slower perceptual analysis of long, relative to short letter-strings. This effect became less apparent as the frequency of the items decreased, since lexical processing became more demanding, and thus took its toll in the form of slower naming.

3.3 General Discussion

Having identified and validated the length effect in Hebrew naming, it still remained to understand why this effect materialised in the first place, in a language with such an opaque orthography. Indeed, length effects have been previously observed in Hebrew (Lavidor, Ellis & Pansky, 2002; Lavidor & Whitney, 2005), but to date, no attention has been given to the influence of word-frequency on length effects in this language. According to current reading models, highly familiar words should be immune to any form of spelling-to-sound inconsistencies (Coltheart & Rastle, 1994; Rastle & Coltheart, 1998; Seidenberg & McClelland, 1989; Plaut et al, 1996; Plaut & Kello, 1998). One study, however, challenged this view, by showing that even in the relatively consistent orthography of English[16], high-frequency words were named more slowly when the level of spelling-to-sound consistency was decreased (Jared, 1997).

Indeed, the data from Experiment 1 clearly showed a significant length effect for high-frequency words in English (22 ms), and even in Spanish (12 ms). Since length effect is reflective of attempted sequential assembly of phonology from print, this finding can be explained in light of the Phonological Hypothesis (c.f. Frost, 1994; 1995), in terms of a 'strategic dilemma' faced by the reader. In a language as transparent as Spanish, any word which cannot be easily recognised via direct lexical retrieval can be assembled using grapheme-to-phoneme conversion rules. In this case the reader faces no dilemma. However in English, and more so in Hebrew, the latter strategy would usually be effortful, time-consuming and is not guaranteed to yield the correct pronunciation. Nevertheless, when faced with a relatively unfamiliar word, the reader is bound to resort to the less efficient sublexical assembly, even in Hebrew, as observed by Frost (1994; 1995).

It has been previously suggested by advocates of the alternative, Visual Encoding Hypothesis that the presence of non-words in the stimulus list might

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[16] English is by no means considered to be a consistent orthography, however in this case, it is more consistent than Hebrew, hence the term 'relatively' must be emphasised.

encourage participants to use phonological assembly to a greater extent than in their absence (Baluch & Besner, 1991; Tabossi & Laghi, 1992). In the present experiments, high- and low-frequency words, and non-words were presented in randomised order. Participants therefore had no knowledge of what type of stimulus was to follow. Moreover, participants were instructed, in the event of an unknown word appearing, to try guessing the correct pronunciation as quickly as possible, but were not told that the stimulus list would contain non-words. Under such conditions, it is likely that the knowledge of the existence of ‘strange’ words might have prompted participants to attempt a sequential assembly of letter-strings, regardless of frequency or length, within the first few milliseconds of exposure. This led to slower naming, most apparent in long high-frequency words in English and more so in Hebrew, but not in Spanish. Interestingly, the magnitude of length effect for high-frequency words seemed to increase systematically with 2% in Spanish, 3% in English, and 12% in Hebrew, parallel to the position of these languages along the orthographic transparency continuum. These findings can therefore be interpreted in accordance with both, the Visual Encoding and the Phonological Hypotheses.

Further investigation into this issue could be conducted in a future study employing numerous different word lengths of high-frequency words in the 3 languages, and possibly also visualising the time-course of activation using electrophysiology. As will be seen in the next chapter, visualising a length effect within areas involved in orthographic processing using fMRI could also shed some light on this issue.

In an attempt to extend previous findings by including a within-subject comparison, in addition to their native languages, bilinguals named words and non-words in English as their second language. The patterns of accuracy in ESL naming were similar to native English naming, whereby phonological mispronunciation was the predominant type of error, and most were made in low-frequency long words. Overall accuracy was, as expected, lower in ESL than in each bilingual group’s native language, and correlation analysis suggested that this was related to language exposure, particularly formal education. In light of previous suggestions that bilingual readers might transfer reading strategies from the native to the second language (Muljani et al, 1998; Wang et al, 2003), it transpires that any differences in the patterns of interactions between frequency, length and lexicality between the two bilingual groups in the present experiment would be reflective of an influence of the native language on ESL naming. Indeed, in addition to phonological errors, the native Hebrew speakers showed a trend towards word substitution errors to a greater extent than the native Spanish speakers. This type of error may reflect reliance on lexical / semantic processing, whereby whole word processing is vulnerable to erroneous recognition of orthographically similar words.

Interestingly however, Spanish readers tended to make more naming errors in short, relative to long non-words. In addition, the observed differences in the RT data between the two groups were in fact in the opposite direction to that which would be expected. Specifically, while Spanish bilinguals showed a similar pattern to that observed in the English monolinguals, the native Hebrew bilinguals showed a stronger modulation of string-length on frequency and lexicality effects, than that seen for the native English speakers, and indeed the native Spanish speakers. In other words, the modulation of string-length was *stronger* in the native Hebrew speakers than in the native Spanish speakers.

This finding can be explained in terms of a ‘compensatory mechanism’, utilised by readers whose native language differs significantly from their second language in levels of orthographic transparency, leading to an exaggerated use of the opposite strategy to the one that would be most efficient in their native language. This suggestion is in keeping with findings of Frost (1994, 1995) who showed that experienced Hebrew readers showed a preference of vowelised Hebrew words, even at the expense of delaying their response by as much as 300 ms, and the greater the phonological ambiguity of the word, the slower the time of making a lexical decision.

An alternative explanation could be that unequal levels of language exposure may have given rise to the present results. The differences between the two bilingual groups emerged as a result of slower naming of long low-frequency words and non-words by native Hebrew speakers, relative to native Spanish speakers, despite similar accuracy levels. Participants’ demographic data, shown in Table 3-1, suggests that although age of acquisition of English was similar for both bilingual groups, as was the relative length of residence in an English-speaking country, the native Spanish speakers had spent significantly more time receiving formal education in English, and had overall more language exposure than the native Hebrew speakers. Given that formal education is related to lexical knowledge (Tainturier, Tremblay & Lecours, 1992), this finding suggests that the less proficient bilinguals may have been using sublexical assembly of English low-frequency words and non-words to a greater extent than more proficient bilinguals, and indeed, the native English monolinguals.

However, two factors render this alternative explanation less plausible; (i) the level of accuracy in ESL was almost identical between the two bilingual groups, and (ii) Hebrew-English bilinguals showed remarkably similar naming latencies for high and low-frequency words between their native Hebrew, and ESL. The present data therefore does not entirely support the view that reading strategies from the native language may be transferred to the less dominant language, however, some kind of influence does seem to emerge, whereby the Hebrew bilinguals may resort to an exaggerated reliance on phonological assembly for reading in a language that carries a higher level of orthographic transparency than their native language. More cross-language studies are clearly needed in order to verify this suggestion. In the present study, Experiments 4 and 5 reported in the next two chapters shed further light on this issue.

Taken together, the results reported above suggest that the 3 languages, arranged along an orthographic transparency continuum, entail different strategies for visual word recognition, as seen by variance in the effects of word-frequency, string length and lexicality on naming latency and accuracy. Specifically, while Spanish words and non-words can be easily read using sublexical assembled phonology, the successful pronunciation of Hebrew letter-strings, in the absence of vowels, requires lexical knowledge, which leads to slower naming of unfamiliar or nonexistent words. As the midpoint of the orthographic transparency continuum, the English orthography permits both strategies to be used; the presence of vowels allows for sublexical assembly of any letter-string, though the different levels of correspondence between orthography and phonology require the reader to rely on larger graphemic units than single letters, and often apply lexical knowledge for correct pronunciation of frequent, infrequent and even nonexistent words.

The behavioural results observed in Experiment 1 replicate and extend previous results (Frost et al., 1987) and can serve as solid background data for the functional MRI experiments described in the next chapter, aimed at investigating the neural correlates of reading strategies in Spanish English and Hebrew.

Chapter 4

How do Different Levels of Orthographic Transparency and Language Proficiency Affect the Brain?

4.1 Introduction

The development of functional neuroimaging techniques has provided a unique opportunity to look into the brains of neurologically intact individuals. When combined with behavioural measures, the ability to visualise neural correlates of cognitive processes presents a great advantage; it can strengthen and extend observed patterns of behaviour beyond their theoretical framework and provide a better understanding of human cognitive function.

Several studies have made use of converging methodology to investigate the neural correlates of reading processes in monolingual participants (reviewed by Price, 2000; Jobard et al, 2003; Price & Mechelli, 2005; Balota & Yap, 2006). As described in Chapter 2, these studies have contributed a great body of knowledge to the field of neuroscience of language, and have given rise to a general consensus, attesting that the process of reading is mediated by a widely distributed network of cortical regions, involving predominantly left inferior frontal, premotor, inferior parietal and superior / middle temporal regions, typically associated with language processing, as well as bilateral occipital and occipito-temporal regions, related to early visual and linguistic processing of written material, respectively. Of particular interest in the current framework, were those studies that attempted to segregate regions involved in semantic, phonological and orthographic processing (e.g. Pugh et al, 1996;

Fiez et al, 1999; Poldrack et al, 1999; McDermott et al, 2003; Wydell et al, 2003; Joubert et al, 2004; Booth et al, 2006; Bick et al, 2008), following earlier observations of differential manifestations of acquired and developmental dyslexia (e.g. Marshall & Newcombe, 1973), as well as those that have looked at cross-language differences in patterns of activation, using monolinguals and multilinguals (e.g. Paulesu et al, 2000; Vingerhoets et al, 2003; Meschyan and Hernandez, 2005; Simon et al, 2006), following observations of differential manifestations of reading impairments in different languages (e.g. Hinshelwood, 1902; Wydell & Butterworth,1999; Beland & Mimouni, 2001).

The behavioural experiments reported in the previous chapter showed that native readers of Spanish, English and Hebrew relied on lexical and sublexical strategies for reading in these languages to different extents, in keeping with their position along the orthographic transparency continuum. However, while the patterns observed in Spanish and English were straightforward, the inversed interactions between frequency and length effects, observed in Hebrew were due to a strong length effect for word trials, particularly high-frequency words. Although Experiment 2 confirmed that slower naming of long words had stemmed from slower visual processing relative to short words, this observation had not been reported previously and required further investigation. Moreover, while reading in English as a second language the native Spanish bilinguals showed a pattern of frequency, length and lexicality effects indicating an efficient adaptation of their reading strategy to the more opaque L2, the Hebrew bilinguals showed a pattern which was suggestive of an exaggerated reliance on phonological recoding for reading in this relatively more transparent language. While it was suggested that this observation was not related to inferior English proficiency but to a ‘compensatory mechanism’ employed by these bilinguals, this novel suggestion required further investigation.

The present chapter reports two experiments, aimed at visualising the different reading strategies employed by bilinguals of Spanish and English, and Hebrew and English at the cortical level. Since a great body of studies concerned with multiple-language processing has been focussed on the neural architecture and localisation of functional processes, the present study employed fMRI as the investigative tool. As outlined in Chapter 2, fMRI; a hemodynamic neuroimaging method provides accurate spatial information on correlates of neural activation, in contrast to electrophysiological methods, which can map the time course of cognitive processes with great precision, but provide relatively little information on their anatomical source.

The first experiment reported below (Experiment 3) was conducted as a pilot with 3 participants, in order to examine the prospect of visualising the neural correlates of reading in bilingual participants, identify putative cortical regions involved in reading in the different languages, and assess the validity and reliability of the experimental design. The second experiment (Experiment 4) was conducted with 24 participants, using word and non-word stimuli, as those used in Experiment 1. It was aimed at replicating the behavioural patterns observed in the native languages, clarifying the unresolved issues, and of course, give rise to new questions.

4.2 Experiment 3:
Visualising the neural correlates of reading in Spanish, English and Hebrew; a pilot study

4.2.1 Introduction

Before embarking on a multi-subject fMRI experiment, it was necessary to ascertain whether the experimental design was appropriate for visualising the neural correlates of visual word recognition in multilinguals. The rationale behind the pilot experiment was therefore to explore the patterns of cortical activation in single subjects. To this end, a simple covert naming task was constructed, which would provide continuous exposure to each language, and would enable fast and simple analysis of the data, before proceeding with the main experiment.

Three participants were included in the pilot; one from each target population (i.e., Hebrew, Spanish and English speakers). These were two bilinguals, native speakers of Spanish and Hebrew, respectively, and one English monolingual. It was expected that all participants would activate cortical regions which have been previously described as being involved in visual word recognition, and that each language would be associated with some distinct regions of activation, reflecting reliance on differential reading strategies, in keeping with their different orthographic properties (e.g. Paulesu et al, 2000, Meschyan & Hernandez et al, 2005; Simon et al, 2006). Moreover, reading in ESL was expected to yield overlapping, but more extensive activation patterns relative to each bilingual’s native language, which would reflect increased cognitive demand for processing a less dominant language (Perani et al, 1996; Kim et al, 1997; Dehaene et al, 1997; Hernandez et al, 2001; Yetkin et al, 1996; Vingerhoets et al, 2003; Briellmann et al, 2004; Meschyan & Hernandez, 2005). The findings from the pilot experiment were expected to provide a basis for Experiment 4.

4.2.2 Method

4.2.2.1 Participants

Two male bilinguals, native speakers of Spanish and Hebrew, respectively, with English as their second language, and one female English monolingual took part in the experiment. The Spanish-English bilingual, aged 31 had been born and raised in Argentina, where he received comprehensive English tuition from the age of 10. He subsequently completed 2 post-graduate degrees in the UK (MSc and PhD; a total of 19 years of formal education). The Hebrew-English bilingual, aged 32, was born and raised in Israel until the age of 10. Subsequently he immigrated with his family to the UK, where he received formal education in English until the age of 18. His higher education was completed in Israel (a total of 19 years). Both participants were therefore considered as fluent speakers and readers of their native language and of English. The monolingual participant, aged 50, was a PhD student (received 17 years of formal education) who had lived in the UK all her life. All participants were 100% right-handed as assessed by the Edinburgh handedness inventory (Olfield, 1971) and had normal or corrected-to-normal vision.

Although fMRI poses no known health risks (Berns, 1999), the use of human subjects in this type of research requires great attention to safety and participant welfare. All participants were therefore given verbal and written information regarding the fundamental principles of fMRI, requirements for entering the MRI environment and scanning procedure (please refer to Appendix 4), and were required to undergo a 3-stage screening procedure. The initial screening (please see Appendix 5) took place at least a week prior to the scanning session, thereby allowing participants to thoroughly review the information sheet and carefully consider their participation. The second screening procedure was applied just before the scanning session began (Appendix 6), followed by receipt of written informed consent by the participants (Appendix 7).

The present study was carried out in accordance with Brunel University's ethical guidelines and procedures for research involving human participants (http://intranet.brunel.ac.uk/registry/minutes/researchethics/ethicsguidelinesv2.pdf), and was given ethical approval by the Research Ethics Committee of the Brunel University School of Social Sciences and Law. In addition, the conduct of fMRI experiments was in accordance with the Rules of Operation of CUBIC (2002; an internal document, approved by the Brunel Ethics Committee).

4.2.2.2 Experimental stimuli and procedure

Two separate reading tasks were constructed for the pilot experiment; a Spanish-English task and a Hebrew-English task. The Spanish-English bilingual was presented with the Spanish-English task and the Hebrew-English bilingual was presented with the Hebrew-English task. The English monolingual was presented with the Spanish-English task in order to maintain an equal time of exposure to the task between the subjects.

Experimental stimuli consisted of 120 words of 4 and 5 letters (please refer to Appendix 8 for the stimulus list), selected according to frequency of occurrence per million, with high-frequency words occurring more than 100 times per million, and low-frequency words occurring less than 10 times per million. Words were selected from a number of databases and appendices of previous studies, as described in Chapter 3. In order to avoid between-language priming effects, none of the chosen words shared semantic characteristics with the other languages. During functional image acquisition participants were instructed to silently read single words appearing at the centre of a screen, or to fixate on a flashing crosshair (baseline task). Words were presented in four alternating blocks, each word appearing for 1.8 seconds, corresponding to the functional image acquisition repetition time. Twenty words were presented in each block. These were high-frequency words in Hebrew or Spanish, high-frequency words in English, low-frequency words in Hebrew or Spanish, and low-frequency words in English. The baseline condition consisted of a crosshair symbol, presented at the centre of the screen. Two fixation blocks of 40 seconds, appeared between the word blocks. Each test thus consisted of four experimental conditions, and one baseline condition. A schematic representation of the scanning sequence is presented in Figure 4-1.

In order to minimise task-switching effects, written instructions appeared prior to the onset of each word block, instructing the participant to read the following words in the corresponding language ("Please read the following words"; "Lee las siguientes palabras; "נא לקרוא את המילים הבאות").

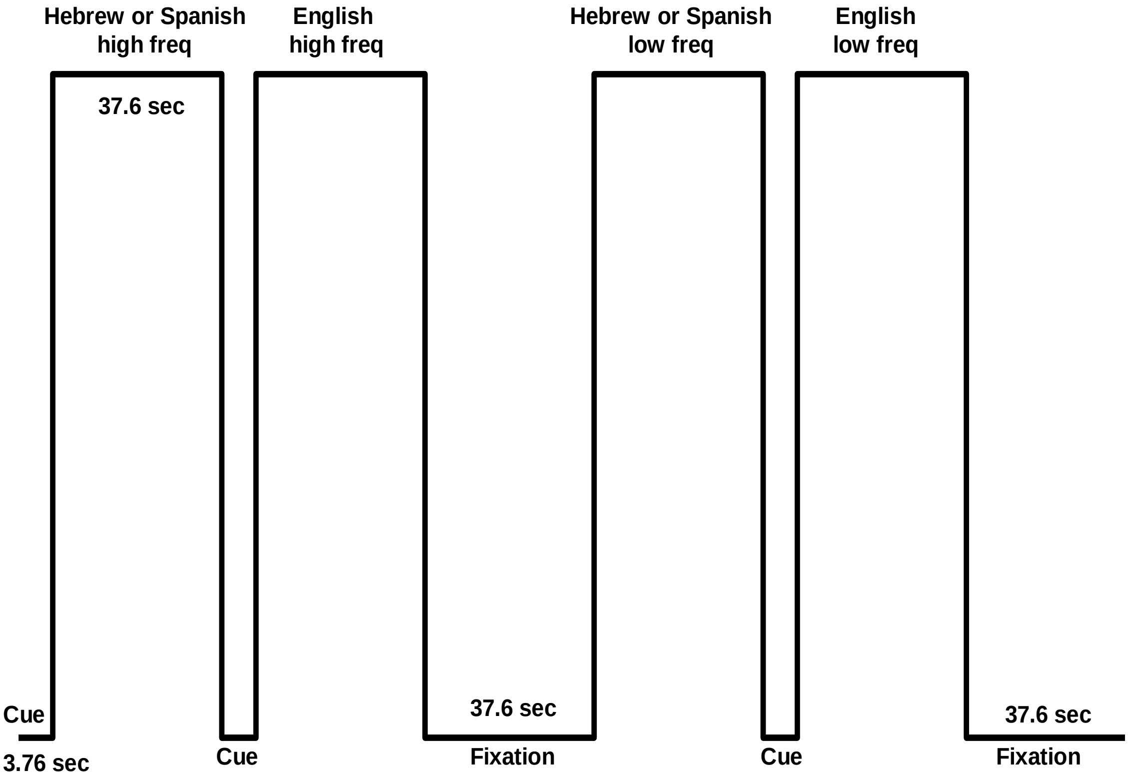

__Figure 4-1__ Schematic representation of experimental design of Experiment 3

4.2.2.3 Functional data acquisition and analysis

The study was conducted using a 3-Tesla Siemens Trio MRI scanner, housed at the Combined Universities Brain Imaging Centre (CUBIC) at Royal

Holloway College London[17]. Participants were positioned supine in the scanner and the head was supported by foam cushions to minimise movement. An alarm buzzer was placed near the participant's right hand, and communication between the examiner and participants was enabled via an intercom system.

The scanning procedure began with a pre-scanning routine used to guide the scanner operator in prescribing slice / volume positions for the experimental scans. Stimuli were projected at 60Hz onto a screen at the back of the scanner, reflected by a mirror positioned above the head of the participant. The projector (Sanyo PLC XP40L, LCD projector) was connected to a Packard Bell laptop displaying stimuli using MS PowerPoint. The laptop was also connected to the scanner so that stimulus transition was controlled by synchronisation pulses transmitted by the scanner at the onset of each volume acquisition.

Functional images were acquired using a T2*-weighted gradient echo planar imaging (EPI) sequence (TR=1800 ms, TE=3000 ms; FOV=192 mm^2; matrix size= 64x64; voxel size=3x3x3 mm). For each participant, 130 volumes were acquired comprising 27 axial slices. In order to identify the precise location of brain activity, high-resolution anatomical images for each participant are typically used. In the present study these images were acquired using a T1-

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[17] The scanner is jointly owned and run by Brunel University, Royal Holloway College, the University of Reading and the University of Surrey, Guilford. It is installed at the Royal Holloway campus, and provides research-dedicated MRI facitilities.

weighted MPR sequence (TR=1830 ms, TE=4.43 ms; FOV 256 mm^2; matrix size=256x256; voxel size=1x1x1 mm), obtained over 176 sagittal slices.

Statistical analysis of functional neuroimaging data was conducted using statistical parametric mapping (SPM; version 2, Wellcome Department of Imaging Neuroscience; http://www.fil.ion.ucl.ac.uk/spm), implemented in MATLAB (version 6.5; Mathworks Inc.). This software applies standard statistical tests to each data point or volume pixel (voxel) in a univariate fashion, producing a map which displays areas of significant activation. These images were overlaid onto the anatomical image of the participants' brain.

Prior to statistical analysis, a pre-processing procedure was applied to the data, in order to minimise the variability between the several images acquired throughout the experiment. Initially, all functional images were 'realigned' to the first image, in order to correct for slight continuous head movements in the course of data acquisition. This was followed by 'coregistration' of the functional images and the participant's anatomical image, for accurate superimposition. In order to accurately identify cortical regions, a process of 'spatial normalisation' was employed. This procedure warps functional and anatomical images to fit a standard brain template, which conforms to the Talairach and Tournoux stereotactic brain atlas (Talairach and Tournoux, 1988). Since this process may skew the data, a final 'smoothing' procedure was applied, using a 6 mm FWHM (full width at half-maximum) Gaussian kernel, which averages out uncorrelated noise, thereby increasing the signal-to-noise ratio.

Following the pre-processing procedure, the experimental design (as shown in Fig. 4-1) was specified in SPM (e.g. Block 1 = Hebrew high-frequency words, Block 2= Hebrew low-frequency words, Block 3 = fixation etc.). The model was smoothed by convolution with SPM's canonical hemodynamic-response function (HRF) in order to account for the typical 6 sec temporal lag in the blood oxygenation level dependent (BOLD) response. Clusters of activated voxels were then identified by the general linear model. Linear contrasts of Reading > Fixation were established for each one of the four experimental blocks, and each was assigned an *F* value. These contrasts compute the general differences between the specified conditions (e.g. high-frequency words relative to fixation). Specific differences between the conditions were then calculated using t-tests, which employ a subtraction approach, thereby enabling the assessment of the direction of the differences between the conditions (e.g. Reading > Fixation relative to Fixation > Reading).

Ten contrasts were explored within and between the languages; these were: within language contrasts (1) L1 high-frequency words > L1 low-frequency words and (2) L1 low-frequency words > L1 high-frequency words, (3) L2 high-frequency words > L2 low-frequency words and (4) L2 low-frequency words > L2 high-frequency words. Between-language contrasts (5) Reading L1 > Reading English and (6) Reading English > Reading L1, (7) L1 high-frequency words > L2 high-frequency words, (8) L2 high-frequency words > L1 high-frequency words, (9) L1 low-frequency words > L2 low-frequency words and (10) L2 low-frequency words > L1 low-frequency words.

The contrast results were superimposed on the stereotaxically normalised anatomical image, in order to identify anatomical regions. Region names were identified using the 'MNI' toolbox in SPM, which conforms to the Talairach and Tournoux stereotactic brain atlas (Talairach and Tournoux, 1988).

4.2.3 Results

Cortical regions found to be activated in response to reading in each language relative to fixation are presented in Table 4-1, displaying peak activation statistics for each activation cluster; number of voxels and regional t values. In the present study effects were reported significant where more than 10 voxels were activated above the threshold of $p<0.001$, corrected for multiple comparisons.

Centres of regions of activation are referenced in x, y, z coordinates in the Talairach and Tournoux (1988) stereotactic atlas, which represent the distance in mm to the right (+) or left (-) of the midline (x axis), anterior (+) or posterior (-) to the anterior commissure (y axis), and superior (+) and inferior (-) to the horizontal plane (z axis).

Table 4-1 *Regions of activation identified in the Reading L1 > fixation and Reading English > fixation conditions*

	Spanish-English Bilingual						Hebrew-English Bilingual						English Monolingual					
	Anatomical region	Voxels	t	Coordinates			Anatomical region	Voxels	t	Coordinates			Anatomical region	Voxels	t	Coordinates		
				x	y	z				x	y	z				x	y	z
L1: Spanish Hebrew or English	*Frontal*						*Frontal*						*Frontal*					
	L PreCG	1018	11.26	-54	-10	48	L PreCG	545	9.60	-54	-2	40	L PrecG	274	8.57	-40	2	54
	L PreCG	1018	11.15	-42	-16	60	L PreCG	545	8.74	-38	-14	68						
	L PreCG	1018	10.78	-56	-6	40	L PreCG	545	7.12	-46	-14	58						
	L IFG	30	6.36	-40	26	-4	L IFG	53	7.84	-60	10	16	L IFG	87	8.70	-48	36	-8
	L IFG	52	5.92	-44	34	2	L IFG	26	6.52	-50	8	-19	L IFG	27	5.80	-52	28	2
	L MFG	62	6.27	-44	32	20							L IFG	27	5.72	-54	20	4
	L MFG	15	6.11	-52	18	20							L MFG	22	6.88	-54	16	26
	L MFG	44	6.57	-46	10	30							L MFG	274	7.27	-50	8	46
							L SFG	25	7.80	-22	52	-14	L SFG	71	7.99	-36	62	-12
							L SFG	21	7.15	-18	58	14						
	L SFG	53	6.51	-8	8	58	L Medial FG	31	6.56	-8	50	42	L SFG	128	7.33	-2	8	70
							L ACG	11	5.68	-8	44	2	L SFG	128	5.87	-8	18	64
							L CG	13	5.54	-6	0	50						
							R PreCG	156	6.36	36	-26	68						
							R PreCG	156	6.19	42	-14	64						
							R PreCG	156	6.08	22	-20	76						
							R PreCG	50	5.92	60	-2	34						
							R PreCG	34	7.47	64	-18	45						
	R IFG	12	6.28	62	6	20	R IFG	31	7.45	62	6	-4	R IFG	11	6.69	56	36	-2
							R IFG	13	5.96	64	6	24						
							R IFG	31	7.45	62	6	-4						
							R MFG	50	5.85	54	8	42	R MFG	37	6.46	40	6	44
														37	6.06	42	6	54
							R SFG	13	5.44	8	6	68						
	Parietal						*Parietal*											
	L IPL	15	6.24	-58	-14	16							L IPL	148	7.50	-42	-60	50
													L IPL	148	6.41	-32	-70	50
							R IPL	30	7.26	46	-36	62						
							R Precuneus	15	6.29	24	-72	40						
	Temporal						*Temporal*						*Temporal*					
	-	-	-	-	-	-	-	-	-	-	-	-	L STG	466	8.74	-58	-54	14
													L MTG	466	9.27	-62	-46	2
													L MTG	466	8.57	-60	-52	-4
													L MTG	48	7.50	-60	-34	-12
													R MTG	14	6.19	66	-34	-4

Abbreviations: L=left, R=right PreCG= pre-central gyrus PostCG=post-central gyrus FG=frontal gyrus
IFG=inferior frontal gyrus SFG= superior frontal gyrus MFG=middle frontal gyrus IPL=inferior parietal lobule
SPL=superior parietal lobule SMG=supramarginal gyrus MTG=middle temporal gyrus STG=superior temporal gyrus
IOG=inferior occipital gyrus MOG=middle occipital gyrus CG=cingulate gyrus ACG=anterior cingulate gyrus

Table 4-1 *Continued*

	Spanish-English Bilingual						Hebrew -English Bilingual						English Monolingual					
	Region	Voxels	t	x	y	z	Region	Voxels	t	x	y	z	Region	Voxels	t	x	y	z
L1 cont.	*Occipital*						*Occipital*						*Occipital*					
	L IOG	651	10.95	-34	-88	-8	L IOG	1439	9.10	-40	-84	-6	L IOG	22	6.21	-28	-88	-16
	L IOG	651	9.59	-36	-88	-16												
	L Lingual G	651	8.43	-14	-96	-20							L Lingual G	22	5.31	-16	-90	-18
	L MOG	14	6.40	-46	-76	-14	L MOG	1439	8.65	-36	-14	58	L MOG	36	6.68	-32	-92	0
							L Cuneus	1439	10.82	-18	-102	0	L Cuneus	91	8.97	-18	-102	0
							L fusiform G	19	7.11	-30	-74	-20						
	R IOG	575	10.86	32	-90	-18	R MOG	981	11.29	36	-88	8	R Cuneus	363	9.71	18	-100	0
	R IOG	575	8.31	36	-84	-26	R MOG	981	10.74	52	-72	-10	R Lingual G	363	8.73	14	-90	-18
	R Fusiform G	575	8.00	20	-92	-18	R MOG	981	10.01	30	-92	0	R Lingual G	363	7.96	10	-96	-8
L2: English	*Frontal*						*Frontal*											
	L PreCG	3037	18.89	-52	-10	48	L PrecG	492	9.05	-54	0	38						
	L PreCG	3037	17.36	-42	-16	60												
	L PreCG	3037	15.76	-52	2	38												
	L IFG	97	7.76	-44	36	2	L IFG	25	8.31	-62	10	16						
	L IFG	34	7.29	-42	26	-6	L IFG	25	7.07	-32	22	-18						
							L IFG	48	6.68	-46	34	-6						
							L IFG	23	6.20	-56	36	4						
							L IFG	23	5.53	-52	28	8						
							L MFG	492	10.32	-48	22	44						
							L MFG	492	8.06	-46	18	36						
							L MFG	112	6.17	-24	26	6						
							L CN	112	6.33	-14	16	4						
	L SFG	60	7.62	-28	66	2	L SFG	74	8.00	-18	56	14						
	L SFG	10	5.41	-16	54	22	L SFG	1840	14.52	-22	52	-14						
	L SFG	60	7.41	-4	4	54	L SFG	50	6.50	-4	14	56						
							L SFG	50	5.96	-2	6	62						
							L SFG	75	6.79	-12	14	72						
							L SFG	75	6.56	14	20	68						
							L SFG	112	6.89	-30	32	6						
	L Medial FG	131	7.50	-4	48	26	L Medial FG	1840	13.42	-8	50	-14						
	L Medial FG	131	5.37	-4	58	26	L Medial FG	1840	11.08	-4	38	-14						
	L Medial FG	61	7.09	-2	46	56	L Medial FG	64	6.79	-6	48	42						
	L Medial FG	61	6.06	0	40	50												
	L Medial FG	20	6.08	-2	-6	66												
	R PreCG	162	8.59	58	-2	42	R IFG	31	7.45	62	6	-4						
	R IFG	118	8.80	64	6	20	R MFG	98	8.76	28	48	-2						
	R IFG	118	8.31	66	-4	10	R MFG	98	7.18	26	56	2						
	R IFG	118	7.88	66	-2	2	R SFG	13	5.44	8	6	68						

Abbreviations:
L=left, R=right
PreCG= pre-central gyrus
PostCG=post-central gyrus
FG=frontal gyrus
IFG=inferior frontal gyrus
SFG= superior frontal gyrus
MFG=middle frontal gyrus
IPL=inferior parietal lobule
SPL=superior parietal lobule
SMG=supramarginal gyrus
MTG=middle temporal gyrus
STG=superior temporal gyrus
IOG=inferior occipital gyrus
MOG=middle occipital gyrus
CN=caudate nucleus

Table 4-1 *Continued*

	Spanish-English Bilingual						Hebrew-English Bilingual					
	Region	Voxels	t	x	y	z	Region	Voxels	t	x	y	z
L2 cont.	*Parietal*						*Parietal*					
							L IPL	10	5.69	-46	-36	48
	L SPL	209	7.57	-20	-74	54						
	L SPL	209	6.64	-12	-76	56						
	L SPL	209	6.40	-36	-68	52						
							L Precuneus	31	7.13	-22	-64	32
							L SMG	100	7.07	-54	-54	26
							R PostCG	257	9.95	50	-36	62
							R PostCG	257	8.47	52	-28	56
							R PostCG	257	7.55	60	-22	46
							R Precuneus	102	8.45	26	-70	42
	Temporal						*Temporal*					
	L MTG	39	6.67	-64	-26	-6	L MTG	37	8.35	-68	-26	-8
							L MTG	26	6.60	-42	-42	4
	L STG	53	7.39	-50	4	-6						
	L STG	11	5.97	-56	-48	18						
	Occipital						*Occipital*					
	L IOG	1933	18.06	-34	-90	-10	L IOG	2936	17.55	-40	-86	-6
	L IOG	1933	14.74	-18	-84	-28	L Cuneus	2936	16.70	-20	-104	0
	L Lingual G	1933	13.03	-12	-98	-22						
	L MOG	14	6.40	-46	-76	-14	L MOG	2936	15.69	-36	-90	-8
	L Fusiform G	21	7.07	-32	-66	-24						
							L fusiform G	23	6.87	-36	-56	-18
	R IOG	1278	16.68	32	-90	-18	R MOG		11.29	36	-88	8
	R IOG		12.92	20	-94	-14	R IOG	1792	11.08	40	-74	-12
	R IOG		11.37	36	-84	-26	R Lingual G	1792	13.42	20	-90	-8
	R MOG	59	8.51	52	-72	-8	R MOG	1792	16.00	36	-88	8

Abbreviations:
L=left, R=right
CG=central gyrus
PreCG= pre-central gyrus
PostCG=post-central gyrus
FG=frontal gyrus
IFG=inferior frontal gyrus
SFG= superior frontal gyrus
MFG=middle frontal gyrus
IPL=inferior parietal lobule
SPL=superior parietal lobule
SMG=supramarginal gyrus
MTG=middle temporal gyrus
STG=superior temporal gyrus
IOG=inferior occipital gyrus
MOG=middle occipital gyrus

4.2.3.1 Within-language effects

4.2.3.1.1 Spanish-English bilingual

As shown in Figure 4-2, reading in Spanish relative to fixation led to bilateral occipital activation encompassing inferior and middle occipital gyri, cuneus, precuneus, lingual gyrus and fusiform gyrus. Frontal activation was almost exclusively left-lateralised with a very large cluster identified in the precentral gyrus, extending ventrally to encompass the middle frontal gyrus. Two clusters were identified within the posterior and anterior regions of the inferior frontal gyrus, as well as three clusters within the middle frontal gyrus (Table 4-1). In the right frontal cortex one small cluster was identified in the inferior frontal gyrus. In addition, a small midline cluster was identified in the superior frontal gyrus.

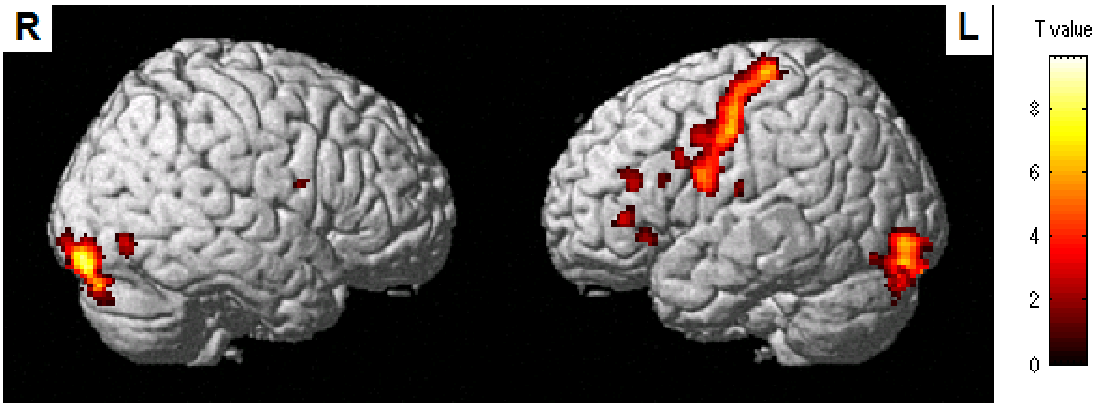


***Figure 4-2** Clusters of significant activation detected while reading in Spanish > Baseline*

Reading high-frequency words relative to low-frequency words did not lead to differences in the pattern of activation in Spanish, however, as shown in Figure 4-3, reading low-frequency words relative to high-frequency words led to extensive activation within the medial frontal gyrus (295 voxels; x=-2, y=46, z=54; $t_{(122)}$=7.23. 53 voxels; x=2, y=-12, z=76; $t_{(122)}$=7.21. 27 voxels; x=0, y=70, x=20; $t_{(122)}$=6.73. 32 voxels; x=4, y=14, z=74; $t_{(122)}$=6.44), as well as the left inferior occipital gyrus (30 voxels; x=-36, y=-90, z=-14; $t_{(122)}$=6.27), left posterior precentral gyrus (54 voxels; x=-16, y=-28, z=70; $t_{(122)}$=7.29) and right middle frontal gyrus (63 voxels; x=30, y=58, z=24; $t_{(122)}$=6.52).

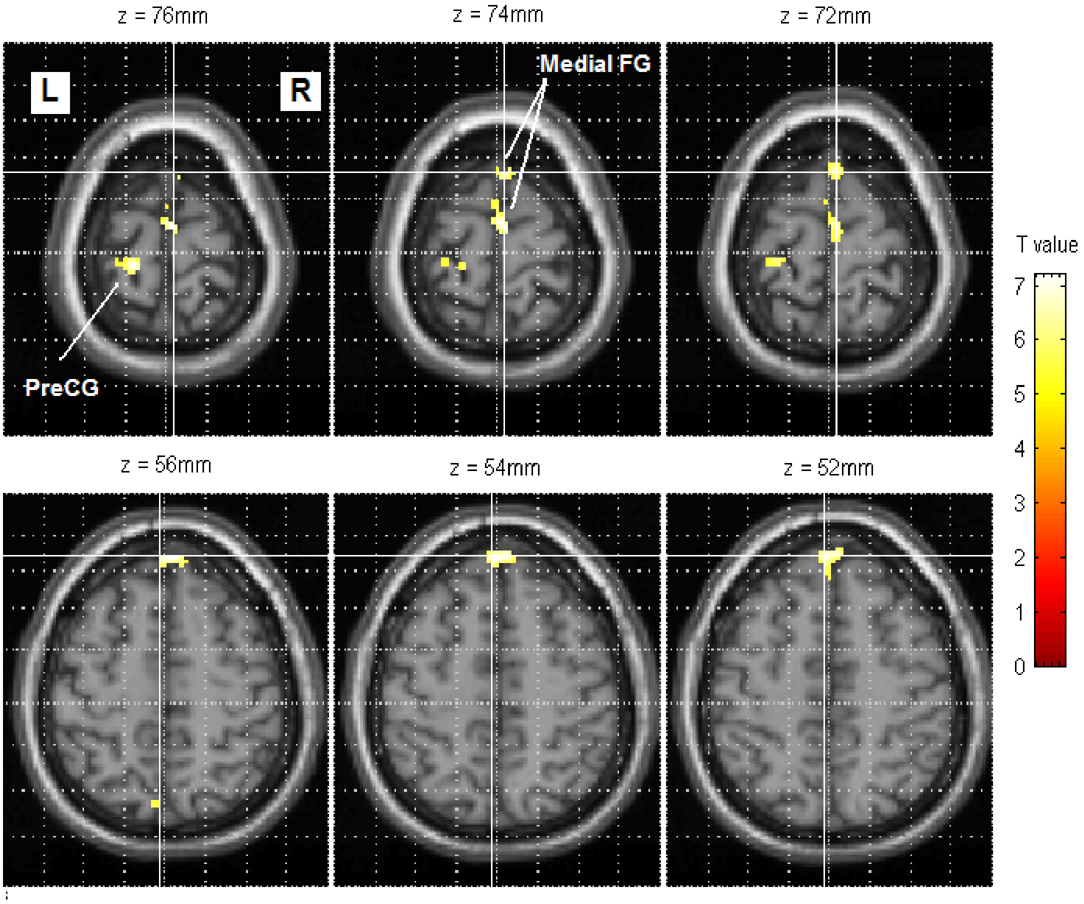


Figure 4-3 *Clusters of significant activation identified while reading low-frequency words relative to high-frequency words in Spanish; Continued below*

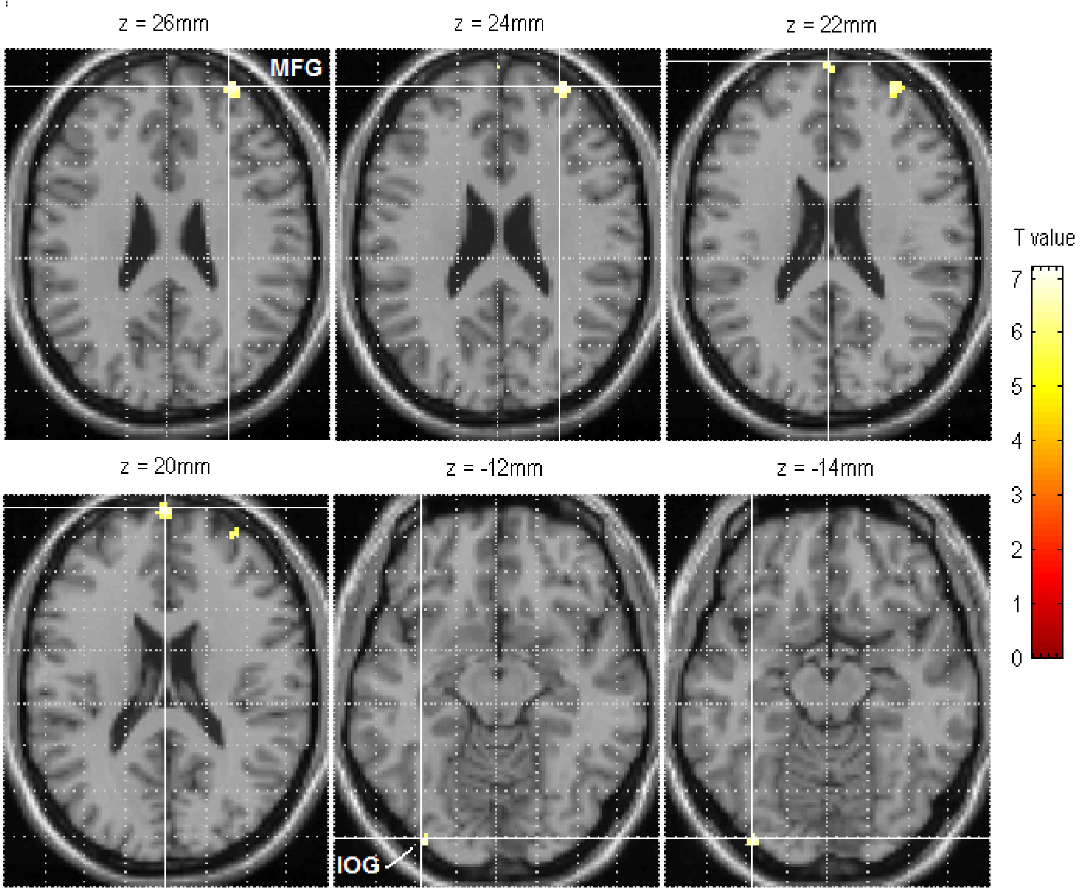


***Figure 4-3** continued*

Reading in ESL led to activation within largely overlapping regions as in Spanish, with extensive bilateral occipital, and left-lateralised precentral activation. Table 4-1 and Figure 4-4 show that the main difference between ESL and Spanish reading were in the spatial extent of activated voxels.

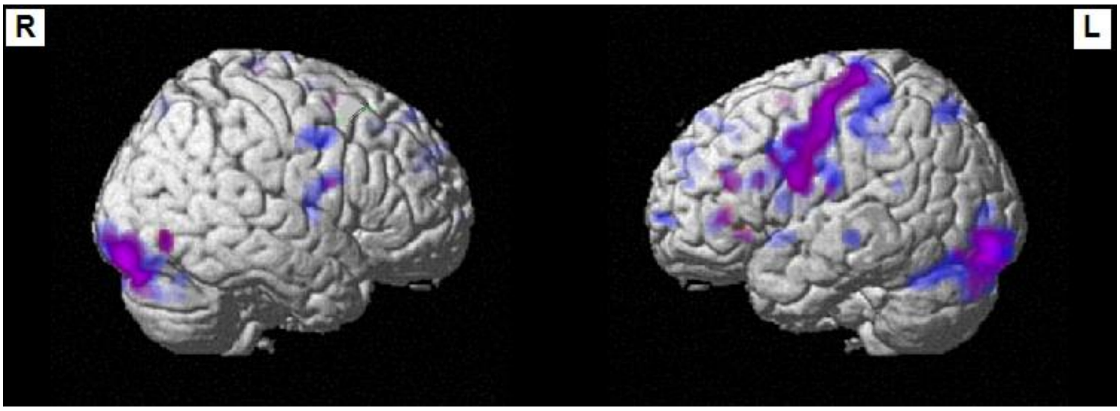


Figure 4-4 Clusters of significant activation identified while reading in Spanish and English. Spanish is represented in red; English in blue; purple clusters represent overlap

As can be seen from Figure 4-5, reading high-frequency words relative to low-frequency words in ESL revealed little difference, with two clusters identified within the posterior and inferior parts of the left precentral gyrus (215 voxels; x=50, y=-10, z=50; $t_{(122)}$=7.62 and 66 voxels; x=-62, y=2, z=22; $t_{(122)}$=7.51, respectively). By contrast, reading low-frequency words relative to high-frequency words led to activation only in the left inferior parietal lobule (41 voxels; x=-48, y=-48, z=42; $t_{(122)}$=6.01).

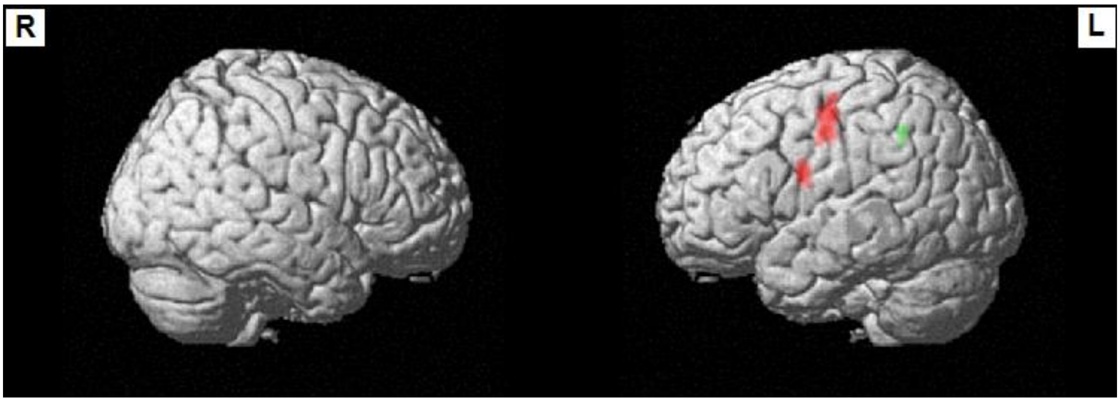


Figure 4-5 Clusters of significant activation identified while reading high and low-frequency words in ESL by Spanish-English bilingual; high-frequency words are represented in red; low-frequency words in green.

4.2.3.2.2 Hebrew-English bilingual

Reading in Hebrew led to extensive bilateral occipital activation, encompassing largely the same regions as identified in Spanish (Fig 4-6). As shown in Table 4-1, frontal activation was considerably more extensive than in Spanish, and predominantly left-lateralised, with a large cluster identified in the precentral gyrus, 2 clusters in the inferior frontal gyrus, 2 in the lateral superior frontal gyrus and 3 clusters around the midline, encompassing medial frontal gyrus, and cingulate cortex. Activation within homologous right lateralised regions was also detected, though this was less spatially extensive.

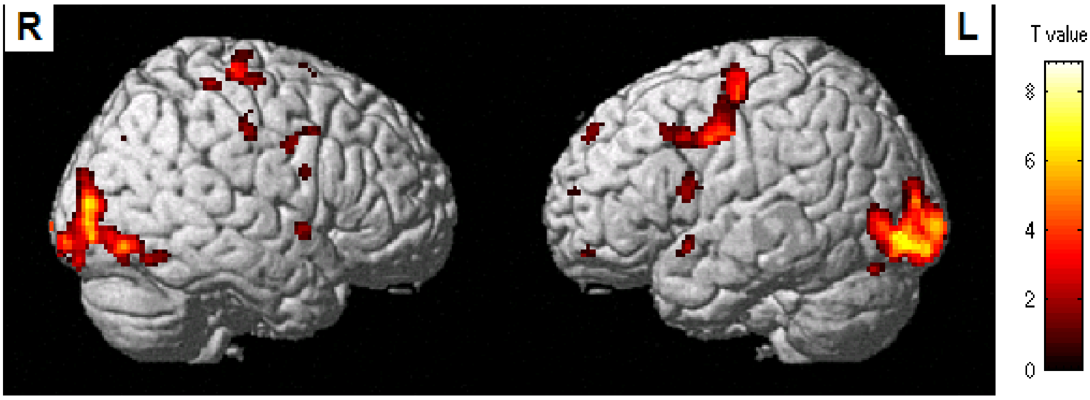


Figure 4-6 *Clusters of significant activation detected while reading in Hebrew > Baseline*

No differences were revealed in patterns of activation between high-and low-frequency words in Hebrew.

Reading in ESL led to bilateral occipital, medial frontal and parietal activation, similar to Hebrew, though as seen in Figures 4-7 and 4-8, activation in these regions were considerably more extensive. In addition, ESL was associated with extensive scattered activation within the anterior inferior frontal, as well as middle temporal cortices, which was not seen in Hebrew (Fig 4-7).

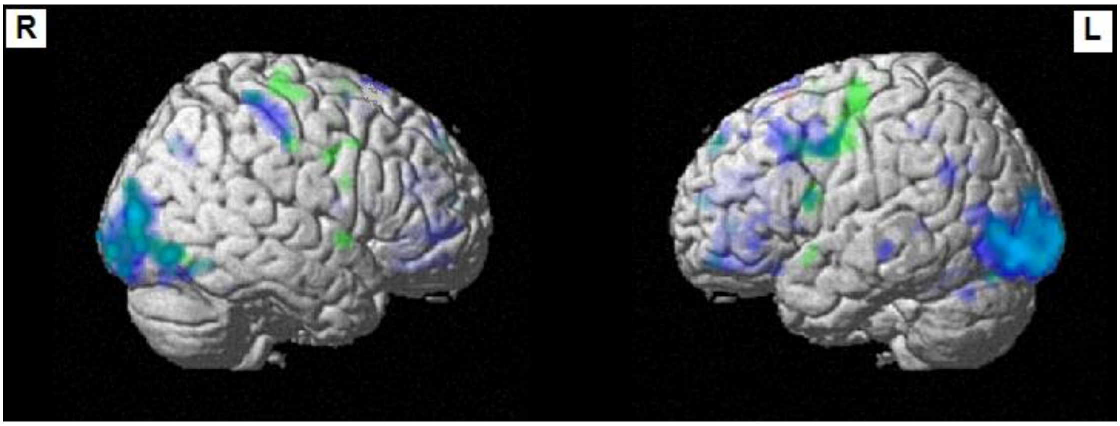


Figure 4-7 *Clusters of significant activation identified while reading in Hebrew and ESL by Hebrew-English bilingual; Hebrew is represented in green; ESL in blue; light blue clusters represent overlap.*

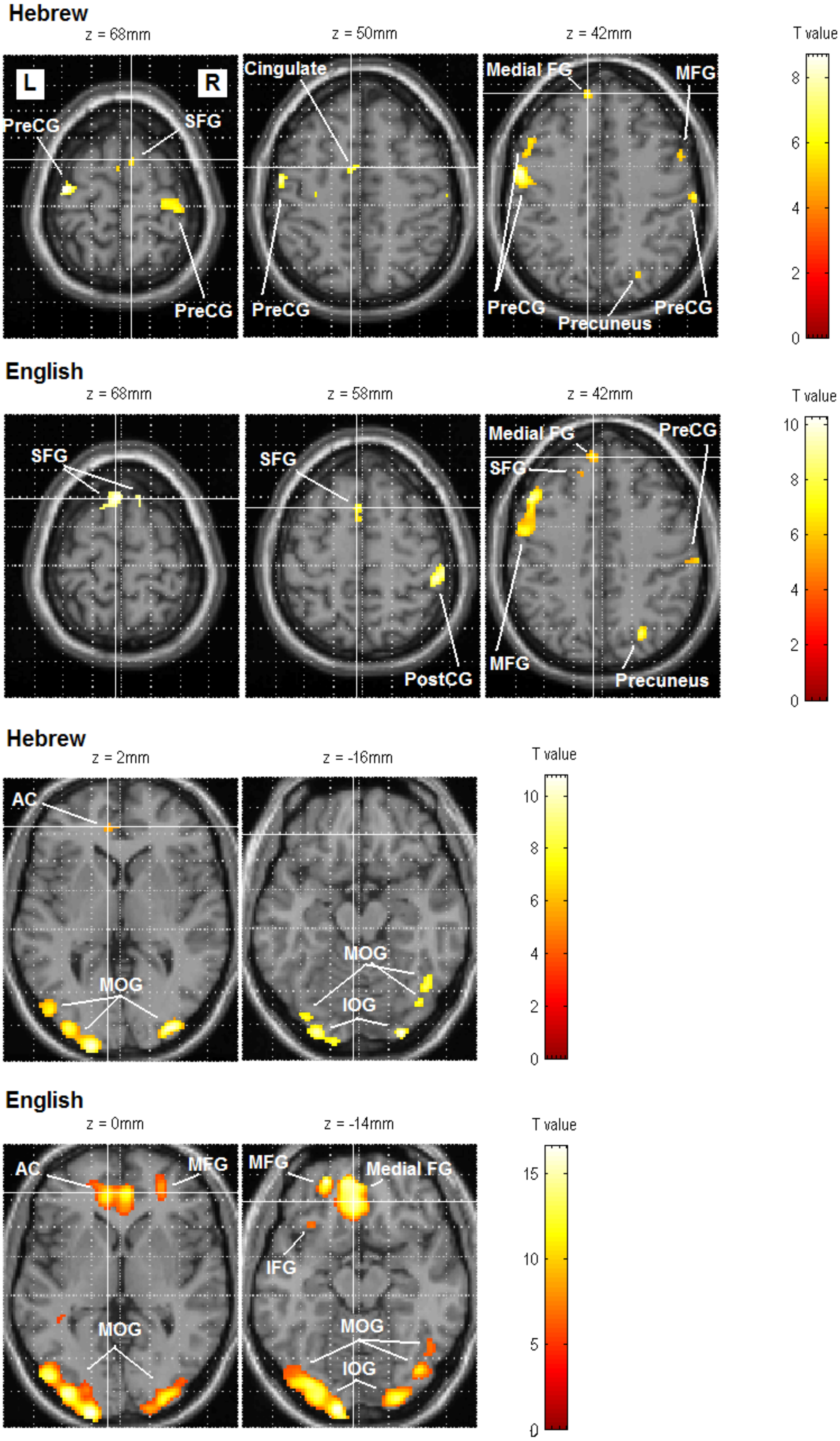
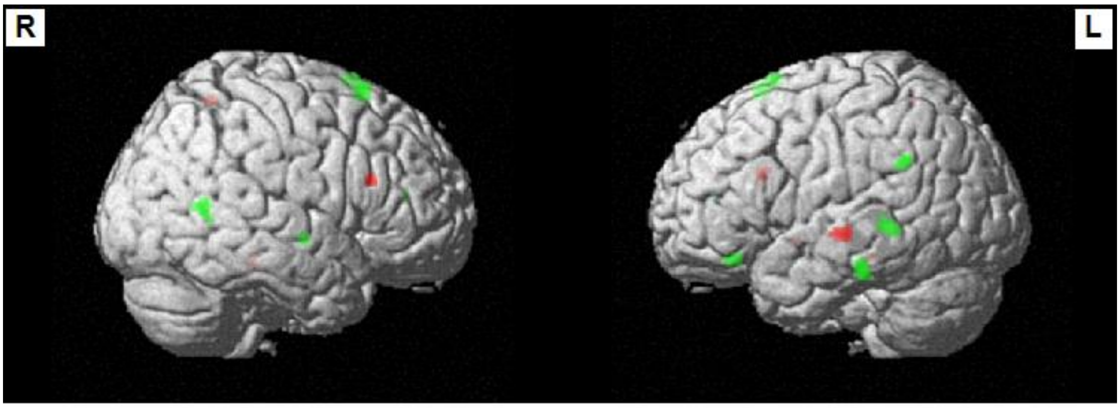


Figure 4-8 *Clusters of significant activation identified within midline structures while reading in Hebrew and ESL by Hebrew-English bilingual*

Reading high-frequency words in ESL relative to low-frequency words revealed very weak activation in the left superior temporal gyrus (30 voxels; x=-64, y=-20, z=-4; $t_{(122)}$=6.41) and in the right inferior frontal gyrus (11 voxels; x=58, y=24, z=22; $t_{(122)}$=5.78). As shown in Figure 4-9, reading low-frequency words relative to high-frequency words led to somewhat more extensive activation within the left posterior superior temporal gyrus, and bilateral middle temporal gyri (left: 32 voxels; x=-66, y=-30, z=-22; $t_{(122)}$=6.42. 28 voxels; x=-70, y=-38, z=0; $t_{(122)}$=6.53. right: 35 voxels; x=60, y=-56, z=8; $t_{(122)}$=6.38. 15 voxels; x=56, y=-8, z=-6; $t_{(122)}$=5.63), left inferior frontal gyrus (16 voxels; x=-48, y=32, z=- 16; $t_{(122)}$=5.73), left inferior parietal lobule (28 voxels; x=-58, y=-48, z=30; $t_{(122)}$=5.68), and around the midline, bilateral superior frontal gyrus (left: 36 voxels; x=-6, y=14, z=70; $t_{(122)}$=6.63. right: 47 voxels; x=12, y=20, z=62; $t_{(122)}$=7.44), and right anterior cingulate gyrus (10 voxels; x=10, y=40, z=14; $t_{(122)}$=5.82).



Midline structures activated during reading of low-freq. words > high-freq. words in English

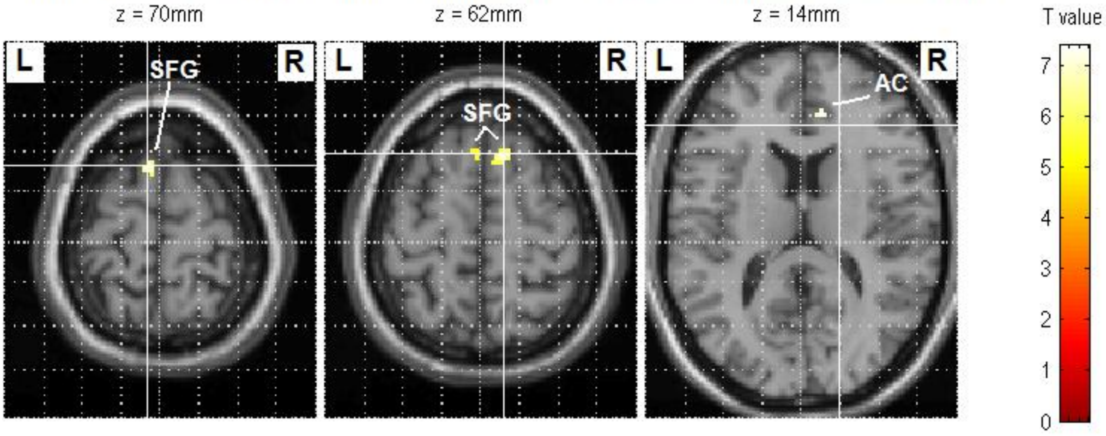


Figure 4-9 *Clusters of significant activation identified while reading high and low-frequency words in English by Hebrew-English bilingual; high-frequency words are represented in red; low-frequency words in green.*

4.2.3.2.3 English monolingual

As in Spanish and Hebrew, reading in English as a native language revealed bilateral occipital activation, and predominantly left lateralised frontal activation, with homologous right hemisphere activation in inferior frontal and middle frontal gyri. As seen in Table 4-1, reading in English also led to strong activation in the left superior and middle temporal gyri, with a small homologous right hemisphere cluster, and left inferior parietal lobule (Fig 4-10).

As in Hebrew, no differences were observed in patterns of activation between high and low-frequency words in English as a native language.

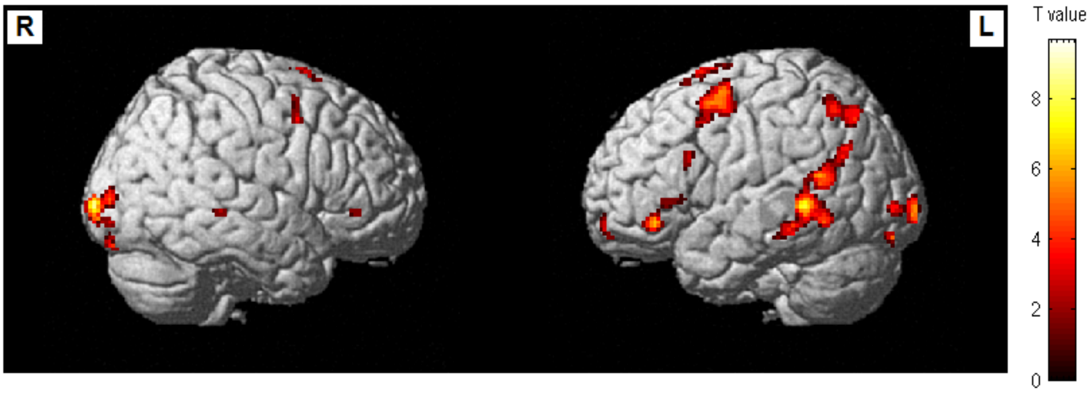
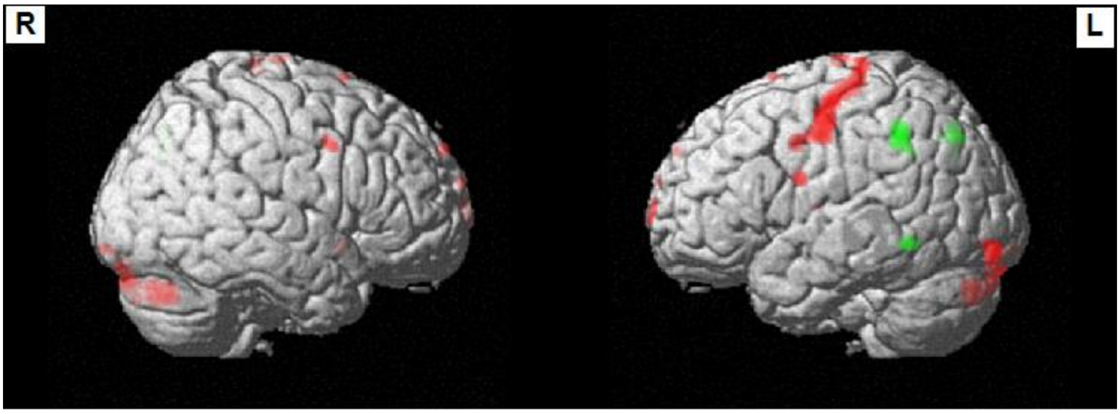


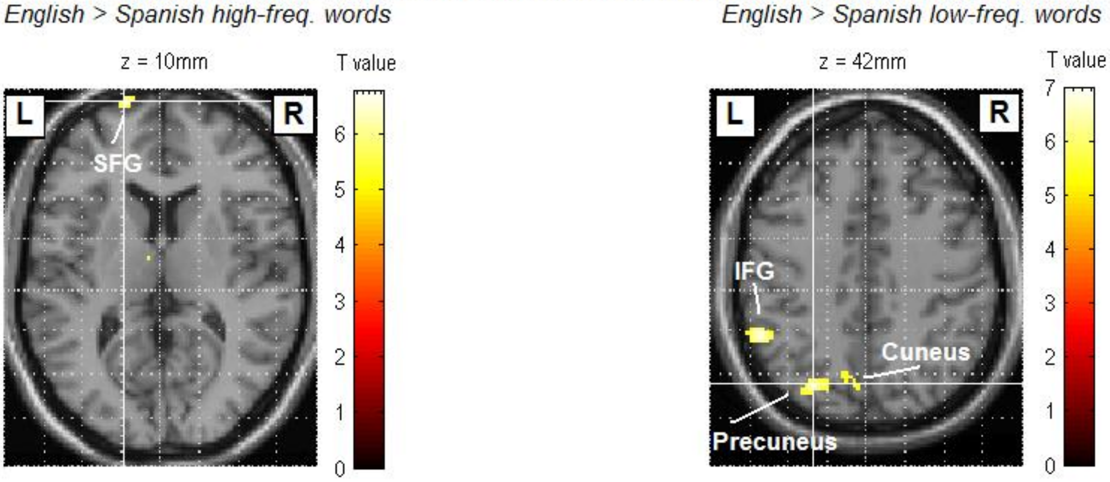
Figure 4-10 *Clusters of significant activation identified while reading in English by English monolingual*

4.2.3.2 Between-language effects

The direct comparison between overall reading in Spanish and ESL revealed no differences in patterns of activation, since the Spanish-English bilingual activated largely the same regions while reading in both languages, as seen in Figure 4-4. However, reliable differences between the two languages emerged in the direct comparison of high and low-frequency words (Fig 4-11), whereby reading in ESL led to more extensive activation within overlapping regions relative to Spanish. Specifically, reading high-frequency words in ESL relative to high-frequency words in Spanish led to extensive activation in the left precentral gyrus (429 voxels; x=-50, y=-12, z=50; $t_{(122)}$=9.03), bilateral inferior occipital gyrus (left: 107 voxels; x=-18, y=-78, z=-28; $t_{(122)}$=7.69, right: 479 voxels; x=16, y=-78, z=-36; $t_{(122)}$=8.40), left middle occipital gyrus (72 voxels; x=-34, y=-90, z=-12; $t_{(122)}$= 7.17), right middle frontal gyrus (27 voxels; x=52, y=6, z=38; $t_{(122)}$=5.77, and around the midline, left superior frontal gyrus (36 voxels; x=-18, y=70, z=10; $t_{(122)}$=6.78). In addition, reading low-frequency words in ESL relative to Spanish revealed a few clusters of activation within the left inferior parietal lobule (123 voxels; x=-54, y=-48, z=46; $t_{(122)}$=7.01), left middle temporal gyrus (32 voxels; x=-62, y=-50, z=-8; $t_{(122)}$=6.93), left cuneus (29 voxels; x=-6, y=-72, z=32; $t_{(122)}$=5.47) and left precuneus (68 voxels; x=-26, y=-72, z=42; $t_{(122)}$=6.47).



Midline structures activated in the direct comparison between English and Spanish


English > Spanish high-freq. words

English > Spanish low-freq. words

Figure 4-11 *Clusters of significant activation identified in the direct comparison of high-frequency words (red) and low-frequency words (green) between ESL and Spanish (ESL > Spanish)*

Comparing reading in Hebrew and ESL directly revealed some differences (Fig 4-7), whereby reading in Hebrew relative to ESL led to bilateral activation in superior and middle temporal gyri (left:104 voxels; x=-60, y=-6, z=-6; $t_{(122)}$=6.77, right: 99 voxels; x=60, y=4, z=-4; $t_{(122)}$=7.95), and bilateral precentral gyrus (left: 28 voxels; x=-54, y=-10, z=40; $t_{(122)}$=6.10, right: 10 voxels; x=40, y=-12, z=32; $t_{(122)}$=6.02), as well as left fusiform gyrus (49 voxels; x=-30, y=-36, z=-22; $t_{(122)}$=6.72), whereas reading in ESL relative to Hebrew led to strong medial frontal activation (411 voxels), encompassing right anterior cingulate (x=2, y=36, z=-8; $t_{(122)}$=8.09) and medial frontal gyri (x=0, y=40, z=-16; $t_{(122)}$=8.66), as well as right lingual gyrus (44 voxels; x=12, y=-86, y=-12; $t_{(122)}$=6.12).

4.2.4 Discussion

The present experiment was aimed at assessing the possibility of visualising the neural correlates of reading in Spanish, English and Hebrew in bilinguals using fMRI, by examining patterns of cortical activation associated with reading in 3 participants, native speakers of each of these languages. Results showed that all 3 participants, while reading in their native languages, activated the left precentral gyrus, previously associated with sub-vocalisation of written stimuli (Fiez et al, 1999; Poldrack et al, 1999; Joubert et al, 2004), particularly of low-frequency items, anterior regions of the IFG and MFG, proposed to subserve semantic processing (Price et al, 1997; McDermott et al, 2003; Booth et al, 2006; Bick et al, 2008), posterior IFG, implicated in sublexical processing (Fiez et al, 1999; Poldrack et al, 1999; McDermott et al, 2003; Booth et al, 2006; Bick et al, 2008), bilateral occipital cortex, encompassing the primary visual cortex, as well as inferior and middle occipital gyri, the lingual gyrus, fusiform gyrus and cuenus, typically associated with early orthographic analysis of written material (Fiez et al, 1999; Poldrack et al, 1999; Wydell et al, 2003; Joubert et al, 2004). In addition, reading in

English as a native language led to activation in the left inferior parietal lobule, encompassing the supramarginal gyrus, typically associated with grapheme-to-phoneme conversion (Fiez et al, 1999; McDermott et al, 2003). A small cluster in this region was also detected in Spanish, but not in Hebrew, suggesting that the differences in the levels of orthographic transparency between the 3 languages may lead to differential patterns of activation.

Interestingly, reading in English led to robust activation within the left middle temporal gyrus, not detected in Spanish and Hebrew, though both bilingual participants showed activation in the same region while reading in ESL, particularly high-frequency words. Activation in the middle temporal gyrus has been previously associated with reading words in English (Pugh et al, 1996; Paulesu et al, 2000; McDermott et al, 2003), suggesting that anterior portions of the temporal cortex might be involved in lexical and semantic processing. Experiment 4, conducted with 24 participants could elucidate whether among the three languages presently investigated, activation in the middle temporal gyrus is unique to English, as findings from the pilot appear to suggest.

In keeping with previous bilingual and multilingual neuroimaging studies, findings of the present experiment showed that reading in English as a second language relative to the native language led to more extensive activation within left frontal, parietal and temporal regions, as well as medial frontal and bilateral occipital regions, reflecting the increased cognitive demand involved in reading the less dominant language (e.g. Perani et al, 1996; Kim et al, 1997; Dehaene et al, 1997; Hernandez et al, 2001; Yetkin et al, 1996;

Vingerhoets et al, 2003; Briellmann et al, 2004; Meschyan & Hernandez, 2005).

The present findings suggest that the chosen experimental design was sensitive enough to reliably detect patterns of cortical activation related to reading in different languages. Moreover, the observed differences in patterns of activation between high and low-frequency words in Spanish suggest that reading low-frequency words required additional resources, such as subarticulatory processing, reflected in activation within the left posterior precentral gyrus (Fiez et al, 1999; Poldrack et al, 1999; Joubert et al, 2004), working memory, seen as activation in the medial frontal gyrus (Fernandez-Duque & Posner, 2001), orthographic processing, reflected by activation in left inferior occipital and occipito-temporal cortex, and additional homologous right middle frontal regions (Fiez et al, 1999; Poldrack et al, 1999; Wydell et al, 2003; Joubert et al, 2004). Similar patterns were detected while reading low-frequency words in ESL in the present experiment, where the Spanish-English bilingual also activated left precentral gyrus as well as inferior parietal lobule. Since these regions have been implicated in sublexical processing, greater activation in these regions while reading low-frequency words may reflect a greater reliance on phonological codes for processing this type of words, especially when they are written in the less dominant language.

The Hebrew-English bilingual showed an even greater reliance on additional resources for reading low-frequency words in ESL, with low-frequency words leading to extensive activation in regions involved in lexical, semantic and working memory processes, such as bilateral middle temporal gyrus, left inferior frontal gyrus and medial frontal cortex, as well as left inferior parietal lobule and left posterior superior temporal gyrus, implicated in phonological processing. The latter observation may hint towards the notion that Hebrew readers may rely on phonological processing for reading in ESL to a greater extent than Spanish readers. In contrast, while reading in Hebrew no differences were detected between the patterns of activation related to high- and low-frequency words, since the type of processing required for reading words in an orthographically opaque language may be more similar in terms of cognitive demands than those required in an orthographically transparent language, and the present experimental design may not be sensitive enough to detect any differences that might have emerged.. Indeed, the baseline task in the present experiment consisted of a crosshair fixation point, which was not visually matched for the experimental stimuli. It is therefore likely that the subtraction analysis eliminated activation which may have been related to frequency effects in Hebrew. This could also account for the absence of effects in the native English monolingual, and suggests that a more stringent approach is needed in order to detect frequency effects in these languages. As described in the next section, this problem was circumvented in Experiment 4 with the inclusion of a non-linguistic baseline task which was visually matched to the experimental stimuli.

Taken together, the findings from the pilot experiment confirm the adequacy of the chosen experimental design for the investigation of the neural correlates of reading in Spanish, English and Hebrew in multilingual participants, and provide solid background for the next experiment.

4.3 Experiment 4:

Naming words and non-words in Spanish, English and Hebrew; an fMRI study

4.3.1 Introduction

Having confirmed that the neural correlates of reading can be visualised using fMRI in bilingual participants, the present experiment was conducted in order to specifically examine the neural correlates underlying the different reading strategies, afforded by the graded levels of orthographic transparency of Spanish, English and Hebrew, with three main goals:

First, the experiment was aimed at distinguishing between cortical regions commonly activated in all native languages and those specifically activated in Spanish, English and / or Hebrew, and assessing whether these could point towards a predominant reliance on reading strategies in accordance with the position of the languages along the orthographic transparency continuum.

Second, the experiment set out to identify regions associated with reading in ESL relative to the native languages, in order to clarify what type of adaptation bilinguals employed for reading in their L2. Visualising the cognitive processes involved in ESL reading could help dissociate between effects of orthographic transparency and language proficiency, as well as shed light on the issue of the exaggerated reliance on phonological processing, proposed to occur while Hebrew bilinguals read in English.

Finally, the experiment aimed to asses the effects of frequency, length and lexicality within regions commonly activated in all languages, as well as some regions associated specifically with each language, in order to elucidate the nature of the unusually strong length effect observed in Hebrew words, and provide new insight beyond inference of the type of processing solely through localisation of function.

Experimental materials consisted of modified versions of the word / non-word naming task used in Experiment 1. As in Experiment 3, participants were required to silently read words and non-words consistently presented in blocks, starting with high-frequency short words, proceeding to high-frequency long words, low-frequency short words, low-frequency long words, and ending with non-words, short letter-strings followed by long letter-strings. This ‘blocked design’ was chosen to ensure continuous exposure to each condition, since the relatively small number of experimental stimuli did not allow for a reliable ‘event-related’ type of analysis (see Henson, Shallice & Dolan, 2000, Pilgrim, Fadili, Fletcher & Tyler, 2002 for discussion regarding event-related vs. blocked fMRI designs). Importantly, since the experimental design used in Experiment 3 was not sensitive enough to detect frequency effects in Hebrew and English as a native language (ENL), the present experiment employed a different type of baseline task, whereby rather than visually fixating on a crosshair, participants were presented with a string of symbols, matched for word and non-word length. This type of baseline was deemed more reliable since it was visually similar to the linguistic stimuli, though did not require reading. Subtracting it from the experimental tasks would therefore minimise irrelevant activation to a greater extent than a crosshair fixation cue.

Results were expected to replicate the behavioural patterns seen in Experiment 1. Specifically, it was predicted that reading in Spanish would be associated with activation in regions reflecting predominant reliance on phonological assembly such as the opercular portion of the left IFG and the left inferior parietal lobule , reading in Hebrew would yield activation in regions predominantly associated with lexical and semantic processing such as the triangular portion of the left IFG and the left superior frontal gyrus, whereas reading in English would show activation patterns suggestive of reliance on both types of processing.

Furthermore, reading in ESL was expected to activate putative language-processing regions to a greater extent than in the native languages, as well as lead to strong activation within regions involved in working memory and attention such as the anterior cingulate gyrus, reflecting a greater processing demand for reading in L2. Moreover, the patterns of reading in ESL relative to each group’s native language were expected to vary in keeping with the type of adaptation required for reading in a language whose level of orthographic transparency differs from the native language. Specifically, the native Spanish readers were expected to show a greater reliance on lexical and semantic processing in ESL relative to Spanish, whereas the native Hebrew readers were expected to show a greater reliance on phonological processing relative to Hebrew. In addition, a direct comparison between the two groups was anticipated to yield a pattern of activation which would clarify whether the Hebrew bilinguals were indeed resorting to exaggerated phonological processing in ESL, relative to their native Spanish counterparts.

Finally, the effects of frequency, length and lexicality within regions associated with reading in each language and the interactions between them were expected to vary in keeping with their position along the orthographic transparency continuum. Similar to findings from behavioural studies (e.g. Forster & Chambers, 1973; Frederiksen & Kroll, 1976; Glushko, 1979; Balota & Chumbley, 1984; Lukatela et al, 1989; Weekes, 1997; Ziegler et al 2001; de Groot et al, 2002; Juphard et al, 2004), systematic increase in neural activation while reading high-frequency words and low-frequency words has been shown to reflect reliance on lexical / semantic processing (Fiez et al, 1999; Paulesu et al, 2000; Wydell et al, 2003; Joubert et al, 2004). In contrast, an increase in activation while reading long relative to short letter-strings has been associated with sequential assembly of print (Wydell et al 2003). Furthermore, increase in activation while reading non-words relative to real words may reflect either type of strategy, depending on the orthography (lexical processing in logographic writing systems such as Chinese, e.g. Siok et al, 2004; phonological processing in alphabetic writing systems with transparent orthography such as Italian, e.g. Paulesu et al, 2000; and Finnish, e.g. Wydell et al, 2003; and both types of processing in less transparent orthographies such as English e.g. Fiez et al, 1999; or French, e.g. Joubert et al, 2004). In the present study, reading in Spanish was therefore expected to give rise to robust length effects and positive strong interactions between these and frequency and lexicality effects. Reading in English was expected to give rise to moderate length effects and interactions, and reading in Hebrew was anticipated to give rise to strong frequency and lexicality effects but no length effects. The present study is the first to specifically asses the magnitude of frequency, length and lexicality effects and the interactions between them in bilinguals of Spanish-English and Hebrew-English using fMRI. It was hoped that visualising these effects at the cortical level using a 3-point comparison could strengthen current findings, and provide solid background for future bilingual and multilingual studies.

4.3.2 Method

4.3.2.1 Participants

Twenty four participants (13 female, 11 male) who had taken part in Experiment 1, were screened to comply with MRI safety regulations and gave informed consent for participation in the present fMRI experiment. All participants were right-handed according to the Edinburgh handedness inventory (Olfield, 1971; mean score 93% ±9) and had normal or corrected-to-normal vision. Eight participants were Spanish-English bilinguals (4 female, 4 male), 8 were Hebrew-English bilinguals (4 female, 4 male), and 8 were English monolinguals (5 female, 3 male). Demographic details of these participants are presented in Table 4-2.

***Table 4-2** Demographic details of Bilingual and Monolingual participants who took part in Experiment 4*

	Native Spanish Speakers (N=8)		Native Hebrew Speakers (N=8)		Native English Speakers (N=8)	
	range	mean (SD)	range	mean (SD)	range	mean (SD)
Age (years)	18-35	27.6 (6.4)	19-33	27.6 (4.4)	18-35	27.1 (6.4)
Formal education (years)						
Overall	13-22	17.6 (3.2)	13-18	15.6 (1.6)	14-22	18.1 (2.9)
Spanish	3-17	12.8 (5.2)	-	-	-	-
Hebrew	-	-	10-16	12.6 (1.9)	-	-
English	1-13	6.4 (3.8)	1-9	4.3 (2.7)	14-22	18.1 (2.9)
Age of acquisition (years)						
Spanish	Native		-	-	-	-
Hebrew	-	-	Native		-	-
English	3-14	7.5 (4.2)	4-10	7.7 (2.4)	Native	
Length of residence (years)						
Spanish-speaking country	4-28	20.8 (9.5)	-	-	-	-
Israel (Hebrew speaking)	-	-	14-26	21.0 (4.2)	-	-
English-speaking country	1-14	6.8 (4.6)	1-10	6.3 (3.1)	Native	
Language exposure (hours per week)						
Spanish	0.5-65	18.9 (21.6)	-	-	-	-
Hebrew	-	-	1.5-70	29.4 (31.1)	-	-
English	65-90	86.9 (8.8)	30-90	75.0 (21.2)	>90	>90

4.3.2.2 Experimental stimuli and procedure

The tests used for the present imaging experiment were modified versions of the behavioural tests used in Experiment 1. Since the word and non-word stimuli were the same as those used for the behavioural experiment, scanning sessions took place at least 10 days after behavioural data collection for each participant. As in Experiment 1, Spanish-English bilinguals were presented with Spanish and English words and non-words, Hebrew-English bilinguals were presented with Hebrew and English words and non-words, and English monolinguals were presented only with English words and non-words.

Stimuli were presented in 6 separate experimental sub-blocks in each language. In addition, 2 types of fixation blocks were included to serve as baseline conditions. In the present experiment the baseline condition consisted of a string of # symbols, which was matched in length to the reading conditions, i.e. 3 symbols (###) for English and Hebrew and 4 symbols (####) for Spanish matched to short letter-strings, and 5 symbols (#####) for Hebrew and English and 6 symbols (######) for Spanish, matched to the long letter-strings.

During functional image acquisition participants were instructed to silently read single words or non-words appearing at the centre of a screen, or to fixate on a single baseline cue at the same position. As described in Experiment 3, in order to ensure accuracy of stimulus-transition timing, stimuli were designed to proceed according to scanner synchronisation pulses. Each trial thus lasted for 1.8 seconds, with each stimulus appearing for 900 ms, followed by a blank screen for another 900 ms. The rapid disappearance of stimuli was to ensure that participants were alert to the rapid onset and offset of the words, and were not reading each word more than once.

Figure 4-12 presents a schematic representation of the experimental design described herein. Participants were exposed to one language at a time. The order of language presentation was counterbalanced across participants. Written instructions indicated the onset of the experiment. These were written in the language that was to follow. Words and non-words were then presented in randomised order within 6 separate sub-blocks, each corresponding to a different lexical condition, containing 15 trials; these were (1) short high-frequency words, (2) long high-frequency words, (3) short low-frequency words, (4) long low-frequency words, (5) short non-words and (6) long non-words. These sub-blocks were presented in the same order across participants, with the 2 baseline sub-blocks (15 short baseline cues and 15 long baseline cues) presented between experimental sub-blocks 2 and 3, and between sub-blocks 4 and 5. This was to enable multi-subject data analysis in SPM (described below). At the end of the first language block written notification was given that the language was about to change. Upon the onset of the second language block a written sentence instructed participants to read the following words in the corresponding language.

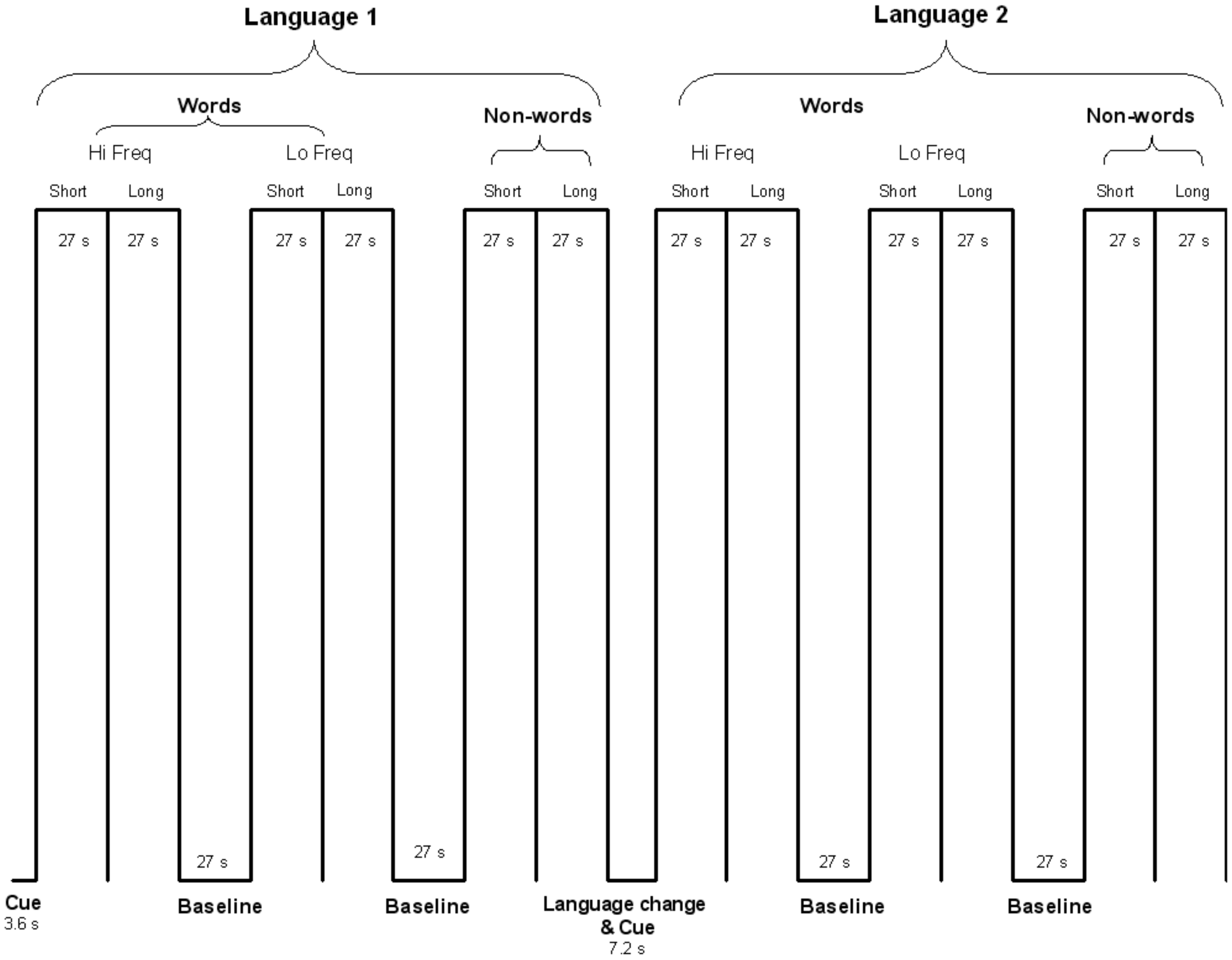


Figure 4-12 *Schematic representation of experimental design of Experiment 4*

4.3.2.3 Functional data acquisition and analysis

Functional images were acquired using a T2*-weighted gradient echo planar imaging (EPI) sequence (TR=1800 ms, TE=3000 ms; FOV=192 mm^2; matrix size= 64x64; voxel size=3x3x3 mm). 255 volumes were acquired for bilinguals and 130 for monolinguals, comprising 27 axial slices. For each participant, a high-resolution anatomical image was acquired using a T1-weighted MPR sequence (TR=1830 ms, TE=4.43 ms; FOV 256 mm^2; matrix size=256x256; voxel size=1x1x1 mm), over 176 sagittal slices.

Data were analysed using SPM2 (Wellcome Department of Imaging Neuroscience; http://www.fil.ion.ucl.ac.uk/spm), implemented in MATLAB (version 6.5; Mathworks Inc), following a pre-processing procedure for each participant individually, as described in Experiment 3. Clusters of activated voxels were identified by the general linear model, and linear contrasts were established for each experimental block. Effects were considered as significant where more than 10 voxels were activated above the threshold of regional t values corresponding to p<0.001 (corrected for multiple comparisons).

In the present experiment fixation blocks were submitted into the analysis as experimental blocks since short and long letter-strings were contrasted with a length-matched baseline.

The analysis aimed to identify regions that were activated in the Reading > Baseline condition, and then to specifically assess the effects of frequency, length and lexicality within those regions. A three-stage approach was therefore used. In the first stage regions of interest (ROI) were defined functionally for each participant individually. The contrast used for ROI definition was Reading > Baseline for English monolinguals, while for bilingual participants these were Reading in each language (L1 or L2) > Baseline masked by overall Reading > Baseline. The masking procedure was employed in order to ensure that the chosen regions were related exclusively to reading and not other cognitive processes.

Common regions of activation for all participants were then submitted into a group fixed-effects analysis. This was performed by entering the data of all participants linearly into a large design matrix in SPM. Regions activated in the group analysis are presented in Table 4-3 for the native languages and Table 4-4 for ESL.

In the third stage a post hoc ROI analysis using MarsBaR (Brett et al, 2002) was employed in order to assess the effects of frequency, length and lexicality within ROIs. This tool, implemented in SPM, enables the exclusive analysis of activation patterns within previously defined regions. The magnitude of the BOLD signal between the different conditions was quantified in terms of the weighted sum of the SPM ‘beta’ parameters (referred to as ‘contrast value [CV]). Within each region of interest, an average CV of all voxels falling within the region was calculated and reported in Tables 4-5 and 4-6. Effects were regarded as statistically significant where CV yielded a regional t values corresponding to p values of <0.05.

In order to compare the patterns of activation between the native languages and ESL, direct comparisons were conducted within each bilingual group, using conjunction analysis, by entering the Reading > Baseline contrasts in the two languages, and masking them by overall Reading > Baseline. This type of analysis identified regions that were commonly activated in two languages, and enabled the measurement of BOLD signal intensity within those regions.

4.3.3 Results

4.3.3.1 Reading in the native languages

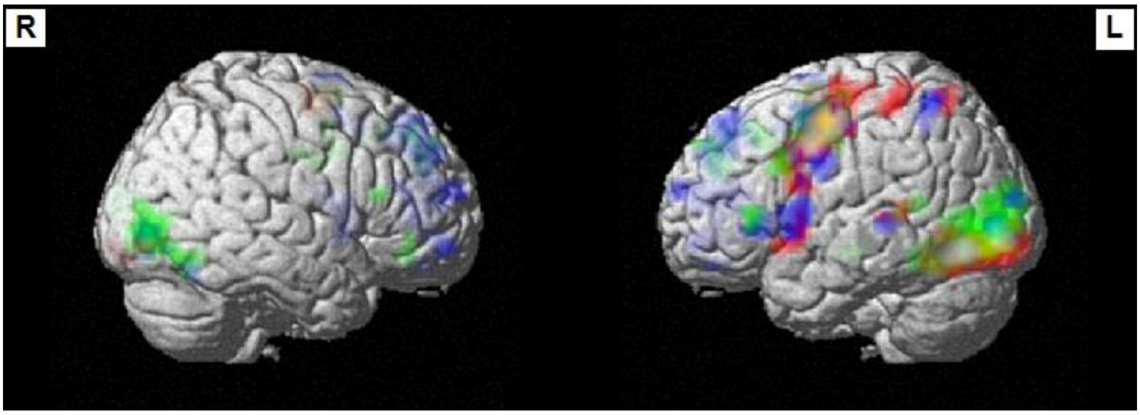


Figure 4-13 *Clusters of significant activation identified while reading in the native languages. Spanish is represented in red; Hebrew in green and English in blue; yellow and white clusters represent overlap between the three languages*

As can be seen in Figure 4-13, group data show large overlap between the three native languages within the left precentral and middle frontal gyri, as well as left inferior and middle occipital cortex. In addition, reading in all languages led to left posterior temporal activation, as well as medial frontal activation, shown in Table 4-3. Importantly, extensive activation was detected within the left inferior frontal gyrus in all languages, though as seen in the figure, these did not overlap; while Spanish was associated with activation in more posterior regions (pars opercularis) of the left IFG, Hebrew was associated primarily with activation in the anterior portion of the gyrus (pars triangularis), and in English, activation was detected within both portions. Moreover, while Spanish and English activated the left inferior parietal cortex, no parietal activation was detected in Hebrew, and while Hebrew and English activated the right superior frontal gyrus and right middle frontal gyrus, no activation was detected in these regions in Spanish. What follows is a detailed description of activation patterns in each language.

Table 4-3 *Regions of activation identified in the Reading L1 > Baseline condition*

Spanish-English Bilinguals						Hebrew-English Bilinguals						English Monolinguals					
Reading Spanish > baseline						Reading Hebrew > baseline						Reading English > baseline					
Anatomical region	Voxels	t	Coordinates			Anatomical region	Voxels	t	Coordinates			Anatomical region	Voxels	t	Coordinates		
			x	y	z				x	y	z				x	y	z
Frontal						*Frontal*						*Frontal*					
L PreCG	**385**	**17.60**	**-51**	**-6**	**54**												
L PreCG	**385**	**10.58**	**-35**	**-12**	**59**	**L PreCG**	**257**	**11.89**	**-54**	**-6**	**48**	**L PrecG**	**272**	**8.96**	**-57**	**-3**	**33**
L MFG	**385**	**12.45**	**-54**	**3**	**39**	**L MFG**	**257**	**9.78**	**-51**	**3**	**51**	**L MFG**	**272**	**10.21**	**-45**	**0**	**36**
						L MFG	**257**	**5.57**	**-54**	**15**	**33**	**L MFG**	**272**	**7.51**	**-48**	**0**	**45**
L op IFG	**10**	**6.40**	**-51**	**9**	**21**							**L op IFG**	**119**	**9.22**	**-57**	**6**	**9**
												L op IFG	**119**	**8.22**	**-45**	**9**	**0**
												L op IFG	**119**	**6.41**	**-51**	**6**	**21**
						L tri IFG	**38**	**6.24**	**-48**	**30**	**3**	**L tri IFG**	**29**	**6.14**	**-45**	**24**	**6**
						L tri IFG	**38**	**5.94**	**-57**	**30**	**9**	**L tri IFG**	**29**	**6.02**	**-51**	**24**	**0**
												L tri IFG	**29**	**5.87**	**-54**	**33**	**0**
						L SFG	71	6.25	-9	45	36	L SFG	21	6.76	-15	63	18
						L SFG	71	5.19	-12	54	39	L SFG	60	6.60	0	3	72
						L CG	49	6.84	-15	24	42	L SFG	60	6.29	0	-3	66
L Medial FG	**66**	**9.88**	**-3**	**-3**	**60**	**L Medial FG**	**41**	**7.11**	**-3**	**-3**	**63**	**L Medial FG**	**60**	**6.74**	**-3**	**6**	**54**
R IFG	12	6.28	62	6	20	R IFG	12	5.89	48	24	15						
												R SFG	19	6.90	30	54	-9
												R SFG	13	5.55	9	39	51
												R SFG	13	5.11	15	36	45
						R CG	38	5.59	30	-12	36	R Medial FG	592	9.00	0	57	-6
						R CG	38	5.31	21	5	39	R Medial FG	592	7.50	5	45	35
						R CG	38	5.29	15	0	45	R Medial FG	592	5.93	9	50	18
						RMFG	18	6.10	45	39	-6	R MFG	37	6.46	40	6	44
						RMFG	18	5.77	39	39	-12	R MFG	37	6.06	42	6	54
												R CN	102	8.94	12	9	9
												R CN	102	6.64	21	9	0

Abbreviations: L=left, R=right PreCG= pre-central gyrus PostCG=post-central gyrus IFG=inferior frontal gyrus tri IFG=triangular IFG op IFG=opercular IFG SFG= superior frontal gyrus MFG=middle frontal gyrus CG=cingulate gyrus CN=caudate nucleus

Figures in bold represent regions that were identified as regions of interest

Table 4-3 *Continued*

Spanish-English Bilinguals						Hebrew -English Bilinguals						English Monolinguals					
Reading Spanish > baseline						Reading Hebrew > baseline						Reading English > baseline					
Region	Voxels	t	x	y	z	Region	Voxels	t	x	y	z	Region	Voxels	t	x	y	z
Parietal						*Parietal*						*Parietal*					
L IPL	**53**	**9.63**	**-51**	**-36**	**60**	-	-	-	-	-	-	**L IPL**	**67**	**8.64**	**-36**	**-54**	**60**
L IPL	**53**	**6.83**	**-39**	**-42**	**69**							**L IPL**	**67**	**5.95**	**-30**	**-51**	**48**
L PostCG	27	6.63	-36	-63	60												
Temporal						*Temporal*						*Temporal*					
L ant STG	**44**	**7.88**	**-54**	**12**	**-9**												
L post STG	16	6.33	-60	-42	9	L post STG	14	5.70	-57	-48	12	L MTG	16	6.61	-63	-33	3
L post STG	16	5.65	-55	-33	6	L post STG	14	4.87	-60	-39	6						
Occipital						*Occipital*						*Occipital*					
L IOG	**443**	**13.18**	**-42**	**-66**	**-15**												
L IOG	443	11.94	-33	-93	-9												
L IOG	443	11.38	-35	-81	-12	**L IOG**	**723**	**14.32**	**-42**	**-78**	**-9**	**L IOG**	**119**	**12.11**	**-42**	**-69**	**-9**
						L MOG	723	12.59	-45	-55	-12	L MOG	61	8.46	-39	-84	3
						L fusiform	723	12.55	-51	-75	0	L MOG	61	7.53	-48	-81	0
												L MOG	18	8.10	-36	-93	15
R IOG	**13**	**7.15**	**42**	**-84**	**-9**	**R IOG**	**191**	**13.29**	**45**	**-81**	**0**						
						R IOG	**191**	**7.10**	**45**	**-55**	**-15**						
						R IOG	**191**	**6.35**	**35**	**-53**	**-15**						
												R MOG	**29**	**6.90**	**45**	**-84**	**0**
												R MOG	**29**	**4.92**	**42**	**-72**	**-9**

Abbreviations: L=left, R=right, ant=anterior, post=posterior, IPL=inferior parietal lobule PostCG=post-central gyrus MTG=middle temporal gyrus STG=superior temporal gyrus IOG=inferior occipital gyrus MOG=middle occipital gyrus

Figures in bold represent regions that were identified as regions of interest

4.3.3.1.1 Reading in Spanish

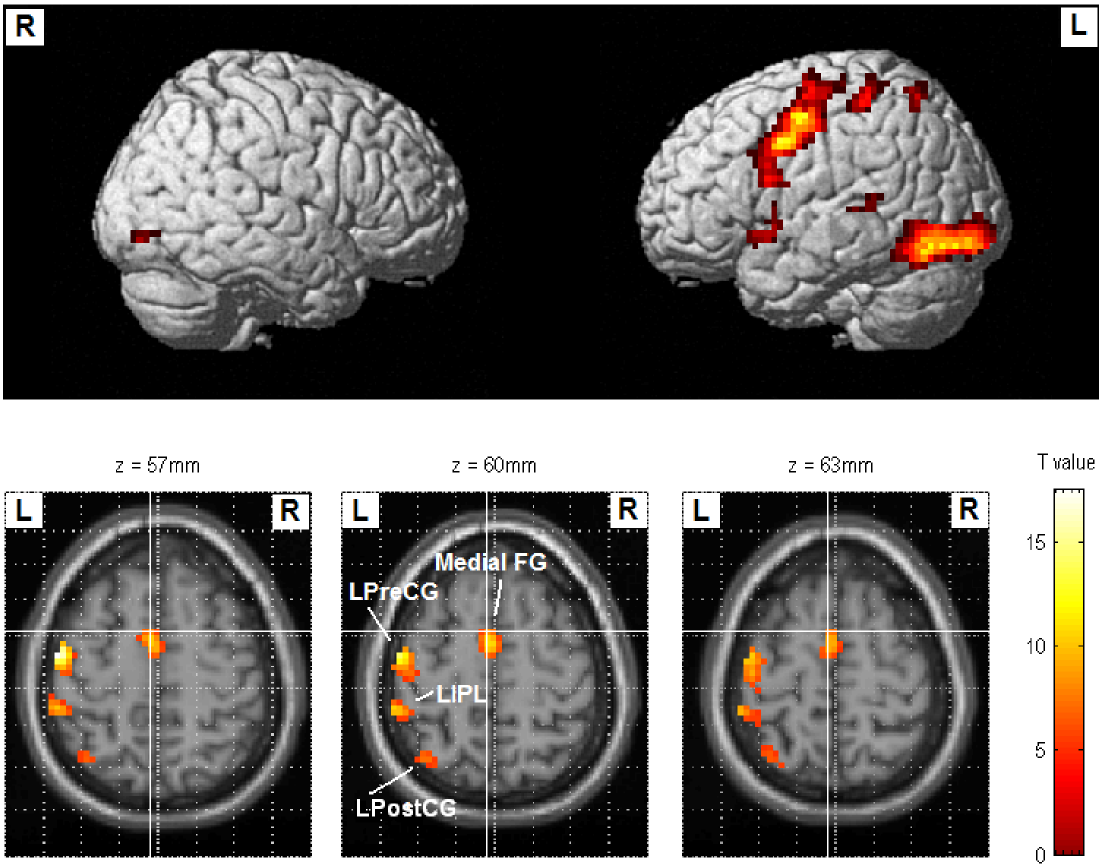


***Figure 4-14** Clusters of significant activation identified while reading in Spanish > Baseline, masked by overall Reading > Baseline*

As shown in Figure 4-14, reading in Spanish relative to baseline led to predominantly left-lateralised activation. A major cluster was identified within the left precentral gyrus, extending ventrally to encompass the middle frontal gyrus. A second major cluster was identified in the left inferior occipital gyrus extending to the middle occipital gyrus, and encompassing the left fusiform gyrus. In addition, smaller independent clusters were identified in the left opercular inferior frontal gyrus, left anterior and posterior superior temporal gyri, left medial frontal gyrus, left inferior parietal lobule, left postcentral gyrus, and right inferior occipital gyrus.

4.3.3.1.2 Reading in Hebrew

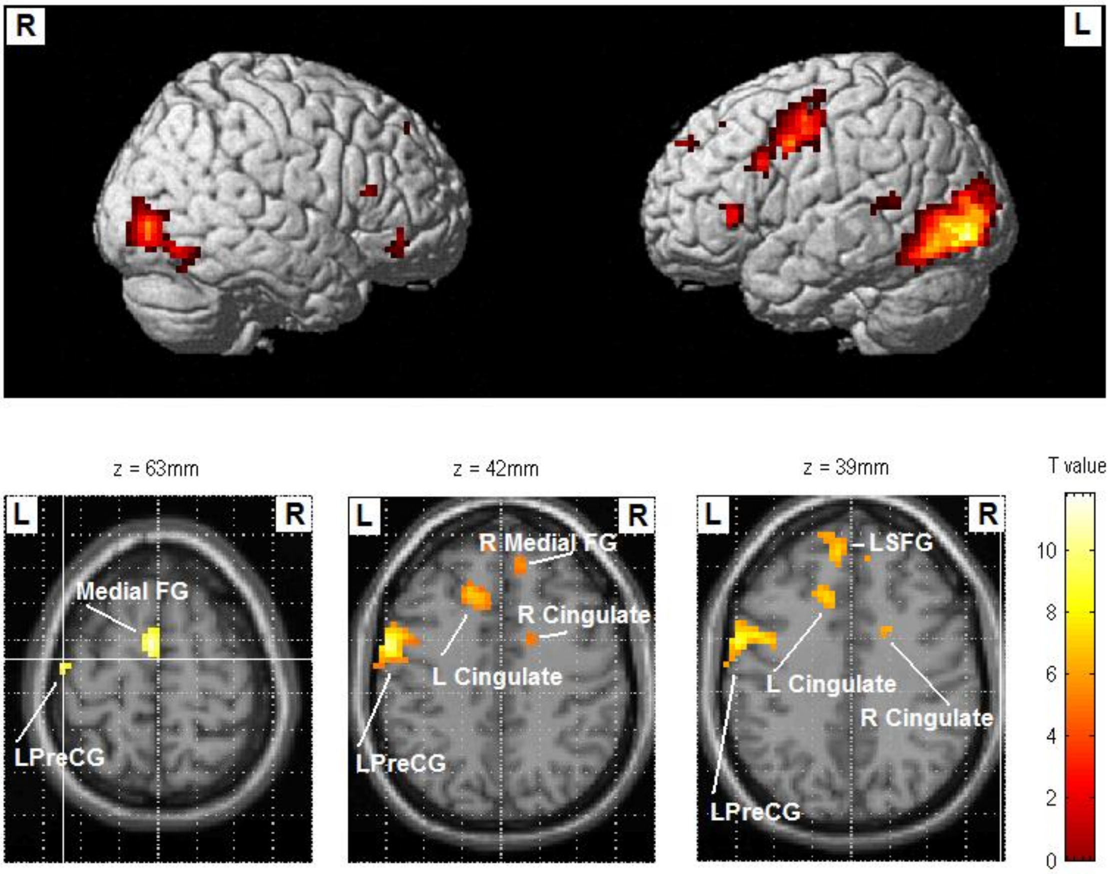


Figure 4-15 *Clusters of significant activation identified while reading in Hebrew > Baseline, masked by overall Reading > Baseline*

Reading in Hebrew relative to baseline led to predominantly left activation, though as seen in Figure 4-15, some contralateral activation was observed in the frontal and occipital cortex. Frontal activation included an extensive cluster within the left precentral gyrus, extending ventrally and anteriorly to encompass the middle frontal gyrus, and smaller clusters within the left inferior frontal gyrus (pars triangularis), right inferior frontal gyrus, and superior frontal gyrus bilaterally. In addition, numerous midline clusters were detected, encompassing bilateral medial frontal and cingulate gyri. In the occipital cortex extensive activation was identified bilaterally, with a large left cluster, encompassing the inferior and middle occipital gyri, extending anteriorly to the left fusiform gyrus, and a somewhat smaller contralateral cluster, encompassing mainly the inferior occipital gyrus. Temporal activation in Hebrew was exclusively left-lateralised with a small cluster identified in the posterior superior temporal gyrus.

4.3.3.1.3 Reading in English as a native language

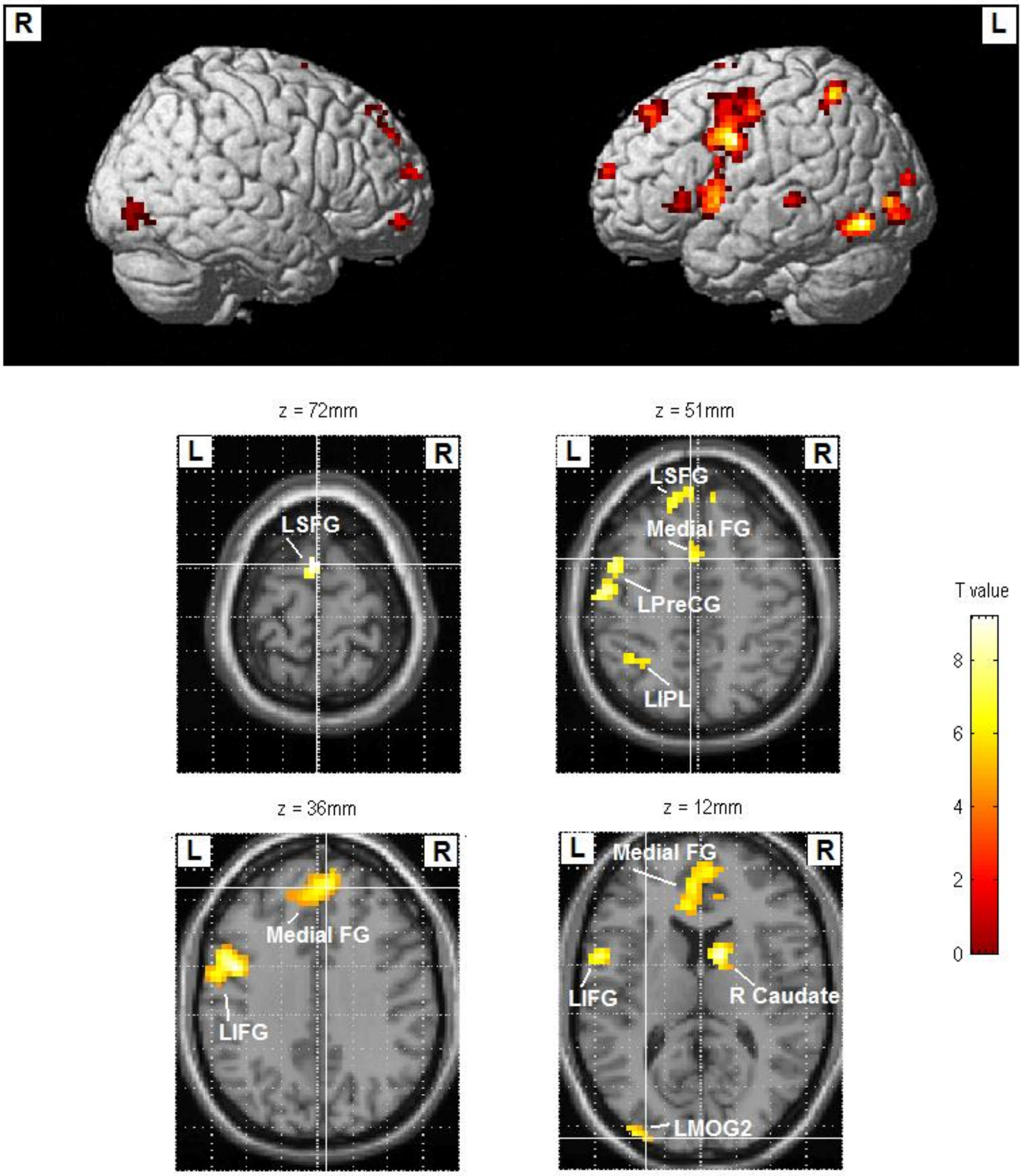


Figure 4-16 *Clusters of significant activation identified while reading in English > Baseline, masked by overall Reading > Baseline*

As shown in Figure 4-16, reading in English relative to baseline led to predominantly left lateralised activation, with an extensive cluster identified in the left precentral gyrus, extending ventrally to encompass the middle frontal gyrus. Considerably wide-spread activation was detected within the medial frontal gyrus bilaterally. Additional frontal activation included a large cluster in the opercular inferior frontal gyrus, a smaller cluster in the triangular portion of the gyrus, and 4 small clusters in the superior frontal gyrus bilaterally. A small cluster was identified in the left middle temporal gyrus, and as in Spanish, a large cluster was identified in the inferior parietal lobule. Occipital activation included 3 independent clusters in the left hemisphere; as shown in Figure 4-16, the largest was located within the inferior occipital gyrus extending to fusiform gyrus, bordering the posterior inferior temporal gyrus. The second cluster was located within the posterior portion of the middle occipital gyrus, and the smallest cluster was located within the superior portion of the middle occipital gyrus, bordering the inferior parietal cortex. In addition, a relatively large cluster was identified in the right hemisphere. Note the spatial extent of this cluster was larger than that seen in Spanish and smaller than that seen in Hebrew.

4.3.3.2 Reading in ESL

Figures 4-17 and 4-18 illustrate clusters of significant activation identified in the Reading ESL > Baseline condition, masked by overall Reading > Baseline by bilingual participants. As shown in the figures, large overlap was seen between each group’s native language and ESL, with two marked differences.

For both groups ESL produced more extensive activation relative to the native language and temporal activation was exclusively right-lateralised.

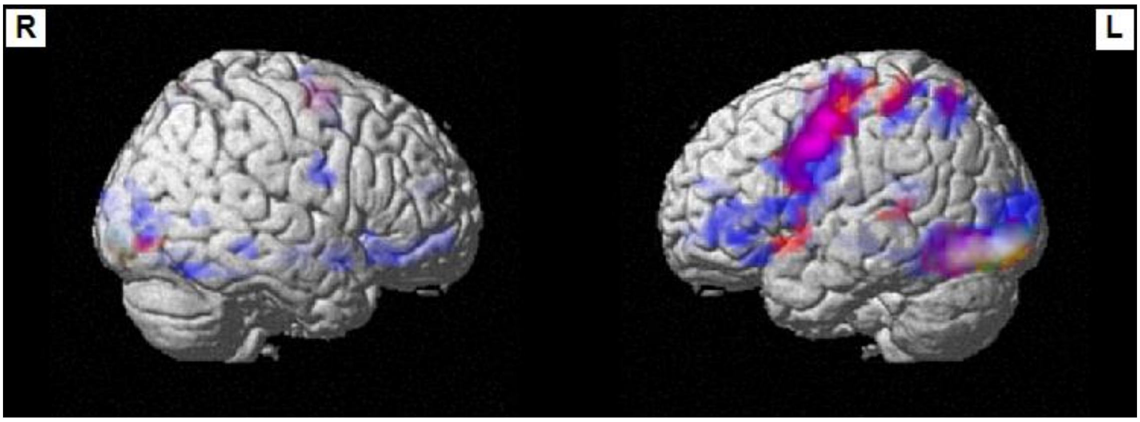


Figure 4-17 *Clusters of significant activation identified while reading in Spanish and ESL by Spanish-English bilinguals; Spanish is represented in red and ESL in blue; purple clusters represent overlap between the languages*

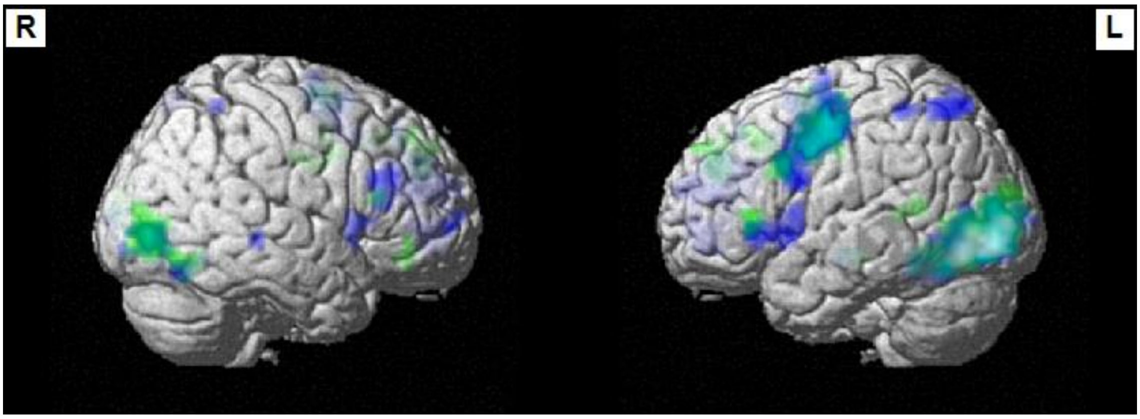


Figure 4-18 *Clusters of significant activation identified while reading in Hebrew and ESL by Hebrew-English bilinguals; Hebrew is represented in green and ESL in blue; light blue clusters represent overlap between the languages*

Figure 4-19 illustrates an overlay of the patterns of activation detected in the two bilingual groups while reading in ESL. As shown in the figure, both groups activated largely overlapping regions within the left hemisphere, though the Spanish bilinguals showed more spatially extensive activation in the left hemisphere relative to the Hebrew bilinguals. Specifically, a noticeable difference between the two groups was seen within the inferior frontal cortex; although some overlap was observed in this region, particularly within the opercular IFG, the Spanish bilinguals activated more anterior portions of the cortex, while the Hebrew bilinguals activated more posterior regions.

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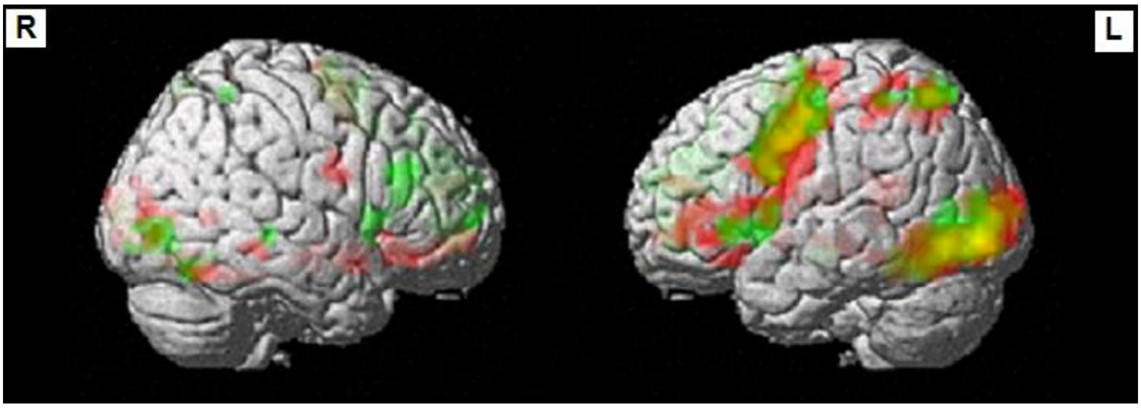

***Figure 4-19** Clusters of significant activation identified while bilinguals were reading in ESL; Spanish-English bilinguals are represented in red, Hebrew-English bilinguals are represented in green; yellow clusters represent overlap between the groups*

Table 4-4 below, summarises the regions of significant activation identified while reading in ESL by bilingual participants

Table 4-4 *Regions of activation identified in the Reading ESL > Baseline condition by Spanish-English and Hebrew-English bilinguals*

Spanish-English Bilinguals						Hebrew-English Bilinguals					
ESL						ESL					
Anatomical region	Voxels	t	Coordinates			Anatomical region	Voxels	t	Coordinates		
			x	y	z				x	y	z
Frontal						*Frontal*					
Left precentral gyrus	***657***	***13.54***	***-54***	***-6***	***51***	***Left precentral gyrus****	***356***	***13.36***	***-57***	***-3***	***48***
Left precentral gyrus	657	11.98	-53	-3	27	Left precentral gyrus	356	9.28	-57	6	24
Left middle frontal gyrus	657	13.51	-57	6	39	Left middle frontal gyrus	356	7.29	-39	-3	55
Left inferior frontal gyrus	**28**	**7.73**	**-42**	**27**	**-15**	Left inferior frontal gyrus	124	7.87	-57	9	6
						Left inferior frontal gyrus	124	7.11	-54	15	-3
						Left inferior frontal gyrus*	***124***	***5.85***	***-51***	***27***	***0***
Left superior frontal gyrus	105	5.72	-3	-6	72						
Left medial frontal gyrus*	***105***	***9.26***	***-3***	***0***	***60***	Left medial frontal gyrus	358	7.88	-3	51	-6
Left medial frontal gyrus	105	8.24	-6	3	51	*Left medial frontal gyrus**	*358*	*7.72*	*-3*	*48*	*18*
Left medial frontal gyrus	41	6.59	-9	42	18	Left medial frontal gyrus	358	7.05	0	33	27
Left superior frontal gyrus	41	6.58	-15	51	21	***Left medial frontal gyrus****	***154***	***8.55***	***-3***	***-3***	***60***
Left medial frontal gyrus	41	5.66	-5	51	21	Left cingulate gyrus	154	7.58	0	9	60
Left cingulate gyrus	73	5.20	-6	6	30	Left cingulate gyrus	154	6.30	-3	12	45
Left anterior cingulate gyrus	19	6.23	-15	48	0						
Left parahippocampal gyrus	39	7.86	-24	-24	-9						
Left caudate nucleus	134	5.99	-24	-39	9						
Left caudate nucleus	22	5.98	-9	18	12						
Left caudate nucleus	22	5.95	-12	9	12						
Right precentral gyrus	18	6.79	66	3	24	Right precentral gyrus	10	5.49	48	-54	57
Right inferior frontal gyrus	53	9.25	33	9	-15	Right inferior frontal gyrus	72	5.91	51	27	15
Right inferior frontal gyrus	53	9.15	27	3	-12	Right middle frontal gyrus	72	6.71	48	27	27
Right inferior frontal gyrus	30	6.90	42	33	-15	Right insula	22	6.61	39	15	6
Right inferior frontal gyrus	30	6.58	45	21	-15						
Right inferior frontal gyrus	30	5.35	51	21	-3						
Right medial frontal gyrus	94	10.48	0	57	-3						
Right medial frontal gyrus	94	8.70	9	60	-3	Right medial frontal gyrus	12	5.33	3	36	42
Right superior frontal gyrus	94	8.95	18	51	-9	Right superior frontal gyrus	19	6.20	27	60	6

Figures in bold represent regions that were identified as regions of interest

Figures in italics represent a significant difference in signal intensity between L1 and ESL, with asterisk annotating significantly stronger activation for ESL relative to L1.

Table 4-4 *Continued*

Spanish-English Bilinguals						Hebrew -English Bilinguals					
ESL						ESL					
Region	Voxels	t	x	y	z	Region	Voxels	t	x	y	z
Parietal						*Parietal*					
Left postcentral gyrus	132	9.02	-30	-57	54	Left postcentral gyrus	110	9.15	-24	-72	60
Left postcentral gyrus	132	8.83	-33	-53	50	Left postcentral gyrus	110	8.21	-39	-57	57
Left postcentral gyrus	***132***	***7.45***	***-21***	***-59***	***57***	**Left postcentral gyrus**	110	7.06	-27	-60	57
						Left postcentral gyrus	18	8.09	-51	-42	57
Left inferior parietal lobule	***68***	***11.19***	***-36***	***-48***	***66***						
Left inferior parietal lobule	**68**	**8.81**	**-54**	**-36**	**48**						
Left inferior parietal lobule	**68**	**5.55**	**-54**	**-35**	**48**						
Temporal						*Temporal*					
Right middle temporal gyrus	**22**	**9.40**	**54**	**-36**	**-12**	**Right middle temporal gyrus**	**14**	**5.58**	**57**	**12**	**0**
Right middle temporal gyrus	12	6.00	39	-60	3						
Occipital						*Occipital*					
Left inferior occipital gyrus	889	15.10	-39	-87	-6						
Left middle occipital gyrus	***889***	***11.07***	***-45***	***-66***	***-9***	Left middle occipital gyrus	600	16.36	-36	-84	-6
Left middle occipital gyrus	889	10.84	-36	-72	-6	***Left middle occipital gyrus***	***600***	***13.39***	***-51***	***-69***	***-9***
						Left Fusiform gyrus	600	10.88	-48	-57	-18
Right middle occipital gyrus	**55**	**6.03**	**33**	**-84**	**9**						
Right middle occipital gyrus	55	5.38	33	-75	3	***Right middle occipital gyrus****	***53***	***9.11***	***48***	***-78***	***0***
Right fusiform gyrus	**154**	**8.06**	**45**	**-57**	**-18**	***Right fusiform gyrus***	***39***	***8.75***	***36***	***-66***	***-18***
						Right fusiform gyrus	39	5.11	36	-54	-12
Right cuneus	55	5.44	21	-84	15	Right lingual gyrus	37	7.37	0	-72	-6
						Right lingual gyrus	37	5.27	9	-72	-9

Figures in bold represent regions that were identified as regions of interest

Figures in italics represent a significant difference in signal intensity between L1 and ESL, with asterisk annotating significantly stronger activation for English relative to L1.

4.3.3.2.1 Spanish-English bilinguals

Reading in ESL by the native Spanish bilinguals led to extensive left lateralised activation. As illustrated in Figure 4-20, very large clusters were detected within the left inferior occipital gyrus, extending anteriorly to encompass the middle occipital gyrus and fusiform gyrus, and within the left precentral gyrus, extending ventrally to encompass the middle frontal gyrus, and inferior frontal gyrus. In the parietal cortex, large clusters were detected within the inferior lobule and postcentral gyrus. In addition, extensive midline activation was detected within the medial frontal gyrus and superior frontal gyrus bilaterally, as well as left cingulate and anterior cingulate gyri. Unlike in Spanish, right activation was prominent, with clusters identified in the inferior frontal gyrus, the precentral gyrus, the middle occipital gyrus, and middle temporal gyrus. In addition, an independent cluster was identified within the right fusiform gyrus.

The direct comparison between Spanish and ESL gave rise to 5 regions, commonly activated in both languages; these were the left precentral gyrus (284 voxels; x=-54, y=-6, z=51; $t_{(1904)}$=13.54), left inferior parietal lobule (21 voxels; x=-54, y=-36, z=57; $t_{(1904)}$=8.00), left postcentral gyrus (25 voxels; x=-36, y=-48, z=66; $t_{(1904)}$=6.63), left inferior occipital gyrus, extending to the middle occipital gyrus and encompassing the fusiform gyrus (380 voxels; x=-45, y=-66, z=-9; $t_{(1904)}$=10.64) and the posterior part of the left medial frontal gyrus (45 voxels; x=-3, y=0, z=60; $t_{(1904)}$=9.26).

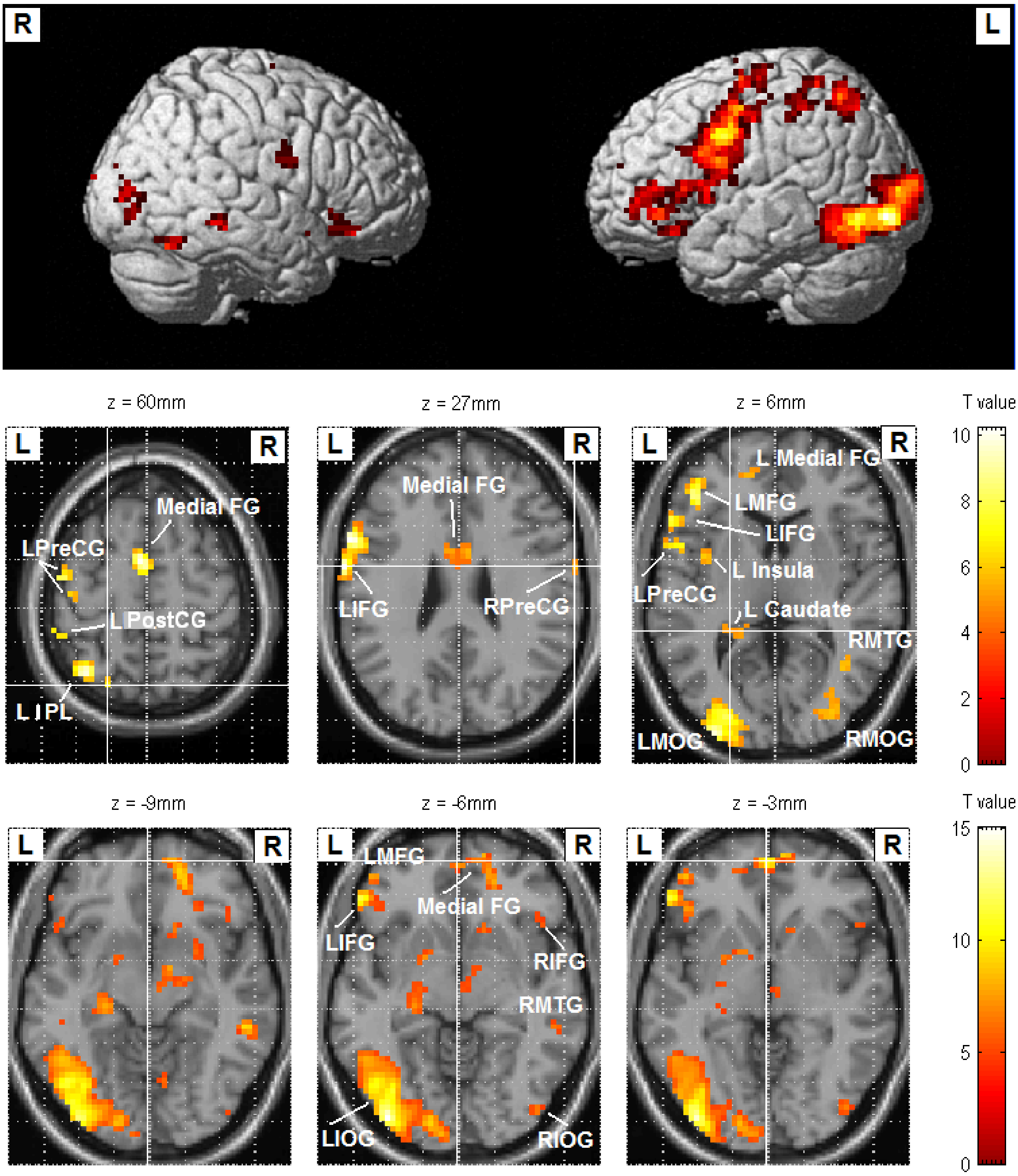

***Figure 4-20** Clusters of significant activation identified while reading in ESL > Baseline, masked by overall Reading > Baseline by Spanish-English bilinguals*

As shown in Table 4-5, reading in Spanish led to significantly stronger activation relative to ESL in the left precentral gyrus, CV=26.00; T=16.91, $p_{(corrected)}<0.001$, left postcentral gyrus, CV=18.95; T=6.24, $p_{(corrected)}<0.001$, and left middle occipital gyrus CV=20.06; T=11.97, $p_{(corrected)}<0.001$. The left inferior parietal lobule also showed greater activation in Spanish relative to ESL, though this difference did not reach statistical significance under the corrected threshold (CV=5.72; T=2.05, $p_{(uncorrected)}=0.02$, $p_{(corrected)}=0.09$). In contrast, reading in ESL led to significantly stronger activation in the medial frontal gyrus, CV=28.26; T=8.94, $p_{(corrected)}<0.001$.

4.3.3.2.2 Hebrew-English bilinguals

As shown in Table 4-4 and illustrated in Figure 4-21, reading in ESL > Baseline by the native Hebrew speakers gave rise to large clusters of activation predominantly in the left hemisphere, though considerably extensive activation was also detected in the contralateral hemisphere. As in the other languages, a large cluster was detected in the left precentral gyrus, extending ventrally to include the middle frontal gyrus. Another large cluster was detected in the left inferior frontal gyrus, encompassing both triangular and opercular portions. In addition, 2 large midline clusters were identified in the left medial frontal gyrus and left cingulate gyrus. In the right frontal cortex smaller clusters were detected within the superior, middle and inferior frontal gyri, as well as precentral gyrus, medial frontal gyrus and insula. In the occipital cortex, a very large cluster was detected within the left middle occipital gyrus including fusiform gyrus, and 3 independent small clusters were detected in the homologous regions on the right. As can be seen form Figure 4-18, large overlap was observed between Hebrew and ESL within the left precentral gyrus and bilateral occipital cortex. The most prominent differences found in ESL reading were parietal and opercular frontal activation, which were not present in Hebrew. In addition, while Hebrew reading gave rise to activation in the left posterior part of the superior temporal gyrus, reading in ESL was associated with activation in the homologous region in the right hemisphere.

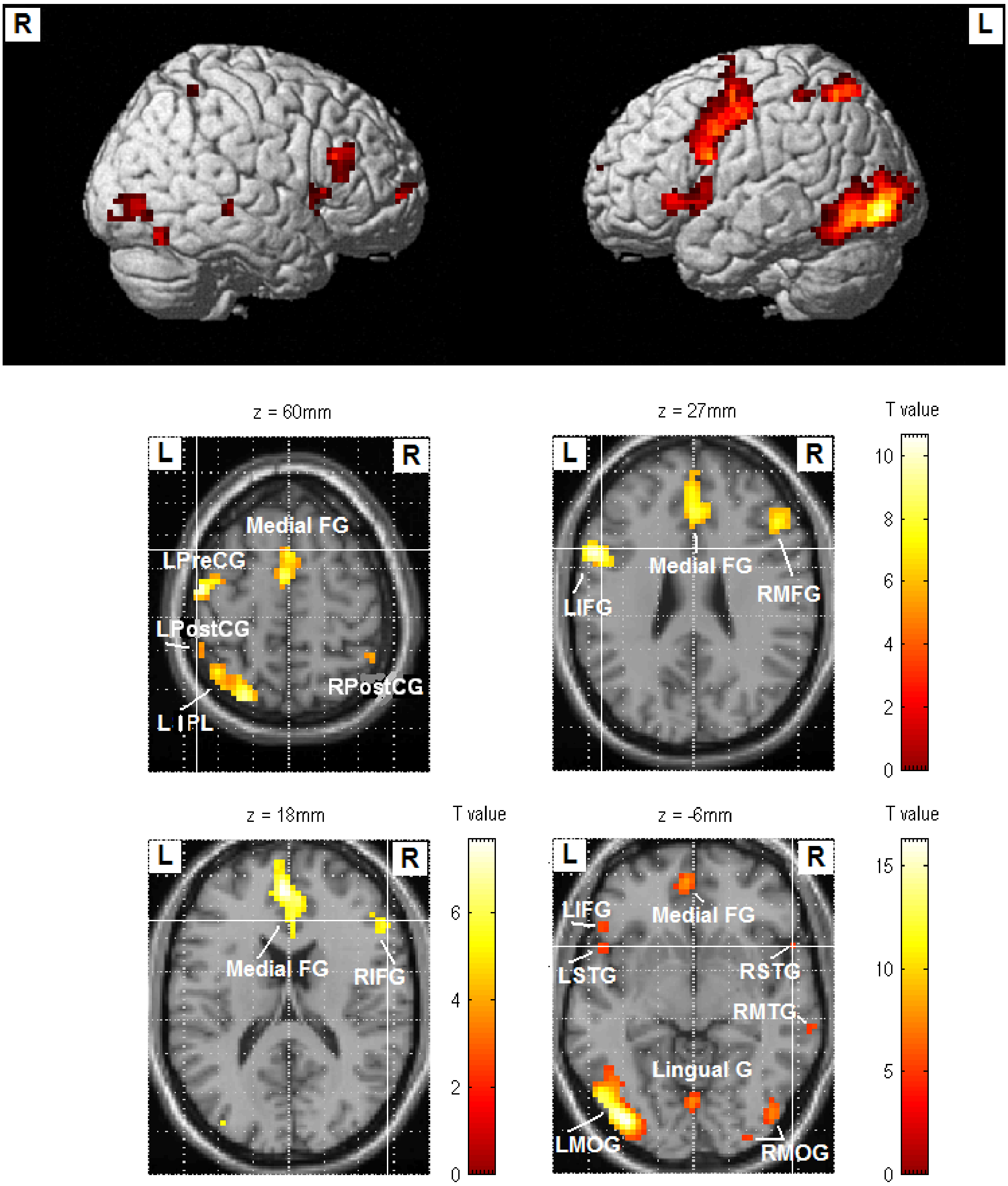

Figure 4-21 *Clusters of significant activation identified while reading in ESL by Hebrew-English bilinguals*

The direct comparison between Hebrew and ESL revealed 7 common regions of activation to both languages; these were left precentral gyrus extending ventrally to the middle frontal gyrus (196 voxels; x=-57, y=-3, z=48; $t_{(1904)}$=11.47), left inferior frontal gyrus (14 voxels; x=-51, y=27, z=0; $t_{(1904)}$=6.03), left middle occipital gyrus including fusiform gyrus(523 voxels; x=-51, y=-69, z=-9; $t_{(1904)}$=14.29), 2 clusters in the medial frontal gyrus (posterior medial frontal gyrus; 35 voxels; x=-3, y=-3, z=63; $t_{(1904)}$=9.11; and anterior medial frontal gyrus; 10 voxels; x=-3, y=48, z=18; $t_{(1904)}$=5.59), and 2 clusters in the right middle occipital gyrus (posterior middle occipital gyrus; 52 voxels; x=48, y=-78, z=0; $t_{(1904)}$=9.11; and fusiform gyrus; 13 voxels; x=36, y=-66, z=-18; $t_{(1904)}$=6.35).

Table 4-7 shows that reading in Hebrew led to significantly stronger activation in the left middle occipital gyrus, CV=4.33; T=3.62, $p_{(corrected)}<0.001$, and the right fusiform gyrus, CV=21.45; T=9.81, $p_{(corrected)}<0.001$, whereas reading in ESL led to significantly stronger activation in the left precentral gyrus, CV=3.89; T=2.68, $p_{(corrected)}<0.03$, the left inferior frontal gyrus, CV=5.29; T=2.54, $p_{(corrected)}<0.04$, the left medial frontal gyrus; posterior CV=19.05; T=7.56, $p_{(corrected)}<0.001$, and anterior CV=42.67; T=14.47, $p_{(corrected)}<0.001$, and in the posterior right middle occipital gyrus, CV=12.90; T=4.87, $p_{(corrected)}<0.001$.

4.3.3.3 Effects of frequency, length and lexicality in the native languages

Common regions in the three languages giving rise to reliable effects of frequency, length and lexicality were the left precentral gyrus, left inferior frontal gyrus (pars opercularis in Spanish, pars triangularis in Hebrew, and both sub-regions in English), and left inferior occipital gyrus including fusiform gyrus. In addition, Spanish and English were found to show reliable effects within the left inferior parietal lobule (not activated in Hebrew). Moreover, the left anterior superior temporal gyrus and left postcentral gyrus, exclusively activated in Spanish were also found to show reliable patterns of effects. Table 4-5 summarises the observed effects of frequency, length and lexicality found within these ROIs. Two additional regions commonly activated in the three languages did not show reliable effects of frequency length and lexicality in all languages; these were the medial frontal gyrus and the right inferior / middle occipital gyrus. In addition, left posterior superior temporal gyrus, commonly activated in Spanish and Hebrew, and the posterior middle temporal gyrus, specifically activated in English showed somewhat inconsistent patterns of effects. The difference in signal intensity between the different conditions in these regions are nonetheless reported, since previous studies have highlighted their role in visual word recognition.

***Table 4-5** Effects of frequency, length and lexicality found within ROIs in the native languages*

		Spanish				**Hebrew**				**English (ENL)**			
		CV	t	p (uncorr)	p (corr)	CV	t	p (uncor)	p (corr)	CV	t	p (uncor)	p (corr)
Left precentral gyrus													
Frequency effects (low – high)	Short words	**2.78**	**5.33**	**<0.001**	**<0.001**	0.72	1.54	0.06	0.32	**1.46**	**3.19**	**<0.001**	**0.007**
	Long words	**4.43**	**8.52**	**<0.001**	**<0.001**	-0.14	-0.30	0.62	0.99	**2.59**	**5.68**	**<0.001**	**<0.001**
Length effects (long – short)	High-frequency words	**1.48**	**2.84**	**0.003**	**<0.001**	0.38	0.8	0.22	0.89	0.56	1.23	0.11	0.64
	Low-frequency words	**3.13**	**6.11**	**<0.001**	**<0.001**	-0.48	-1.04	0.14	0.59	1.69	3.73	**<0.001**	**<0.001**
	Non-words	**3.14**	**6.12**	**<0.001**	**<0.001**	-0.54	-1.17	0.89	1.00	-0.53	-1.2	0.87	1.00
Lexicality effects (nw – wrds)	Short letter-strings	**4.86**	**5.38**	**<0.001**	**<0.001**	**4.18**	**5.17**	**<0.001**	**<0.001**	**3.56**	**4.50**	**<0.001**	**<0.001**
	Long letter-strings	**6.53**	**7.24**	**<0.001**	**<0.001**	**3.21**	**3.96**	**<0.001**	**<0.001**	0.25	0.32	0.38	0.99
Left triangular inferior frontal gyrus													
Frequency effects (low – high)	Short words	**-**	**-**	**-**	**-**	**2.58**	**4.16**	**<0.001**	**<0.001**	1.41	1.75	0.04	0.31
	Long words	**-**	**-**	**-**	**-**	**1.96**	**3.15**	**<0.001**	**0.004**	2.01	2.50	0.006	0.06
Length effects (long – short)	High-frequency words	**-**	**-**	**-**	**-**	0.33	0.52	0.30	0.88	**2.51**	**3.12**	**0.001**	**0.006**
	Low-frequency words	**-**	**-**	**-**	**-**	-0.3	-0.48	0.68	0.89	**3.11**	**3.90**	**<0.001**	**<0.001**
	Non-words	**-**	**-**	**-**	**-**	**1.48**	**2.35**	**0.01**	**0.04**	**2.10**	**2.61**	**0.005**	**0.03**
Lexicality effects (nw – wrds)	Short letter-strings	**-**	**-**	**-**	**-**	**4.92**	**4.57**	**<0.001**	**<0.001**	**5.63**	**4.05**	**<0.001**	**<0.001**
	Long letter-strings	**-**	**-**	**-**	**-**	**7.84**	**7.27**	**<0.001**	**<0.001**	**4.22**	**3.03**	**0.001**	**0.01**
Left opercular inferior frontal gyrus													
Frequency effects (low – high)	Short words	0.37	0.45	0.33	0.94	**-**	**-**	**-**	**-**	1.41	2.34	0.01	0.09
	Long words	1.34	1.63	0.05	0.31	**-**	**-**	**-**	**-**	**1.86**	**3.09**	**0.001**	**0.009**
Length effects (long – short)	High-frequency words	1.44	1.78	0.04	0.23	**-**	**-**	**-**	**-**	**1.66**	**2.76**	**0.002**	**0.01**
	Low-frequency words	**2.41**	**2.98**	**0.002**	**0.01**	**-**	**-**	**-**	**-**	**2.12**	**3.54**	**<0.001**	**0.002**
	Non-words	**3.44**	**4.22**	**<0.001**	**<0.001**	**-**	**-**	**-**	**-**	**2.36**	**3.90**	**<0.001**	**<0.001**
Lexicality effects (nw – wrds)	Short letter-strings	2.62	1.83	0.03	0.21	**-**	**-**	**-**	**-**	2.61	2.50	0.006	0.06
	Long letter-strings	**5.63**	**3.95**	**<0.001**	**<0.001**	**-**	**-**	**-**	**-**	**3.55**	**3.39**	**<0.001**	**0.003**
Left inferior parietal lobule													
Frequency effects (low – high)	Short words	**5.21**	**5.38**	**<0.001**	**<0.001**	**-**	**-**	**-**	**-**	**6.65**	**6.66**	**<0.001**	**<0.001**
	Long words	**8.17**	**8.43**	**<0.001**	**<0.001**	**-**	**-**	**-**	**-**	**9.88**	**9.90**	**<0.001**	**<0.001**
Length effects (long – short)	High-frequency words	0.91	0.92	0.18	0.69	**-**	**-**	**-**	**-**	-1.42	-1.40	0.90	1.00
	Low-frequency words	**3.87**	**4.05**	**<0.001**	**<0.001**	**-**	**-**	**-**	**-**	1.81	1.83	0.03	0.25
	Non-words	**4.10**	**4.31**	**<0.001**	**0.004**	**-**	**-**	**-**	**-**	-3.24	-3.30	0.99	1.00
Lexicality effects (nw – wrds)	Short letter-strings	**10.98**	**6.54**	**<0.001**	**<0.001**	**-**	**-**	**-**	**-**	**17.34**	**10.03**	**<0.001**	**<0.001**
	Long letter-strings	**14.41**	**8.59**	**<0.001**	**<0.001**	**-**	**-**	**-**	**-**	**10.47**	**6.04**	**<0.001**	**<0.001**

Figures in bold highlight statistically significant effects

***Table 4-5** continued*

		Spanish				**Hebrew**				**English (ENL)**			
		CV	t	p (uncorr)	p (corr)	CV	t	p (uncor)	p (corr)	CV	t	p (uncor)	p (corr)
Left postcentral gyrus													
Frequency effects (low – high)	Short words	**5.06**	**5.01**	**<0.001**	**<0.001**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
	Long words	**7.12**	**7.04**	**<0.001**	**<0.001**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Length effects (long – short)	High-frequency words	1.72	1.68	0.05	0.26	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
	Low-frequency words	**3.77**	**3.78**	**<0.001**	**<0.001**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
	Non-words	**6.10**	**6.11**	**<0.001**	**<0.001**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Lexicality effects (nw – wrds)	Short letter-strings	**13.12**	**7.48**	**<0.001**	**<0.001**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
	Long letter-strings	**19.82**	**11.32**	**<0.001**	**<0.001**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Left anterior superior temporal gyrus													
Frequency effects (low – high)	Short words	1.16	1.57	0.06	0.30	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
	Long words	0.83	1.13	0.13	0.56	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Length effects (long – short)	High-frequency words	1.03	1.43	0.08	0.45	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
	Low-frequency words	0.70	1.00	0.14	0.59	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
	Non-words	1.26	1.78	0.04	0.20	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Lexicality effects (nw – wrds)	Short letter-strings	**3.92**	**3.07**	**0.001**	**0.006**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
	Long letter-strings	**4.71**	**3.70**	**<0.001**	**<0.001**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Left middle / inferior occipital gyrus / fusiform gyrus													
Frequency effects (low – high)	Short words	**6.44**	**11.40**	**<0.001**	**<0.001**	**1.62**	**4.26**	**<0.001**	**<0.001**	**3.56**	**5.83**	**<0.001**	**<0.001**
	Long words	**6.48**	**11.46**	**<0.001**	**<0.001**	**1.67**	**4.41**	**<0.001**	**<0.001**	**4.08**	**6.68**	**<0.001**	**<0.001**
Length effects (long – short)	High-frequency words	0.69	1.20	0.11	0.57	**1.49**	**3.93**	**<0.001**	**0.003**	0.55	0.89	0.19	0.72
	Low-frequency words	0.71	1.35	0.09	0.56	**1.55**	**4.10**	**<0.001**	**<0.001**	1.07	1.76	0.04	0.31
	Non-words	1.07	2.05	0.02	0.16	-0.33	-0.89	0.81	0.99	**2.02**	**3.27**	**<0.001**	**0.004**
Lexicality effects (nw – wrds)	Short letter-strings	**11.49**	**11.71**	**<0.001**	**<0.001**	**5.88**	**8.96**	**<0.001**	**<0.001**	**9.49**	**8.97**	**<0.001**	**<0.001**
	Long letter-strings	**12.23**	**12.50**	**<0.001**	**<0.001**	**2.19**	**3.32**	**<0.001**	**0.002**	**11.91**	**11.22**	**<0.001**	**<0.001**

Figures in bold highlight statistically significant effects

4.3.3.3.1 Spanish (Fig. 4-22)

As shown in Table 4-5, strong effects of frequency were found in the left hemisphere, within the precentral gyrus, inferior occipital gyrus, inferior parietal lobule and postcentral gyrus. In all those regions the effect was greater for long, relative to short words (though this difference was not significant in the left inferior occipital gyrus). Length effects were found within the precentral gyrus, opercular inferior frontal gyrus inferior parietal lobule and postcentral gyrus, and the increase in signal intensity within these regions was greater for low-frequency words relative to high-frequency words, and for non-words relative to real words. Lexicality effects were observed in all 6 regions of interest, all of which showed a greater difference for long, relative to short letter-strings.

These findings indicate that within the left precentral gyrus, opercular inferior frontal gyrus, inferior parietal lobule, and postcentral gyrus, the effects of frequency were modulated by string length and within these, as well as the anterior portion of the left superior temporal gyrus, length effects were modulated by lexicality, as observed in the behavioural data in Experiment 1.

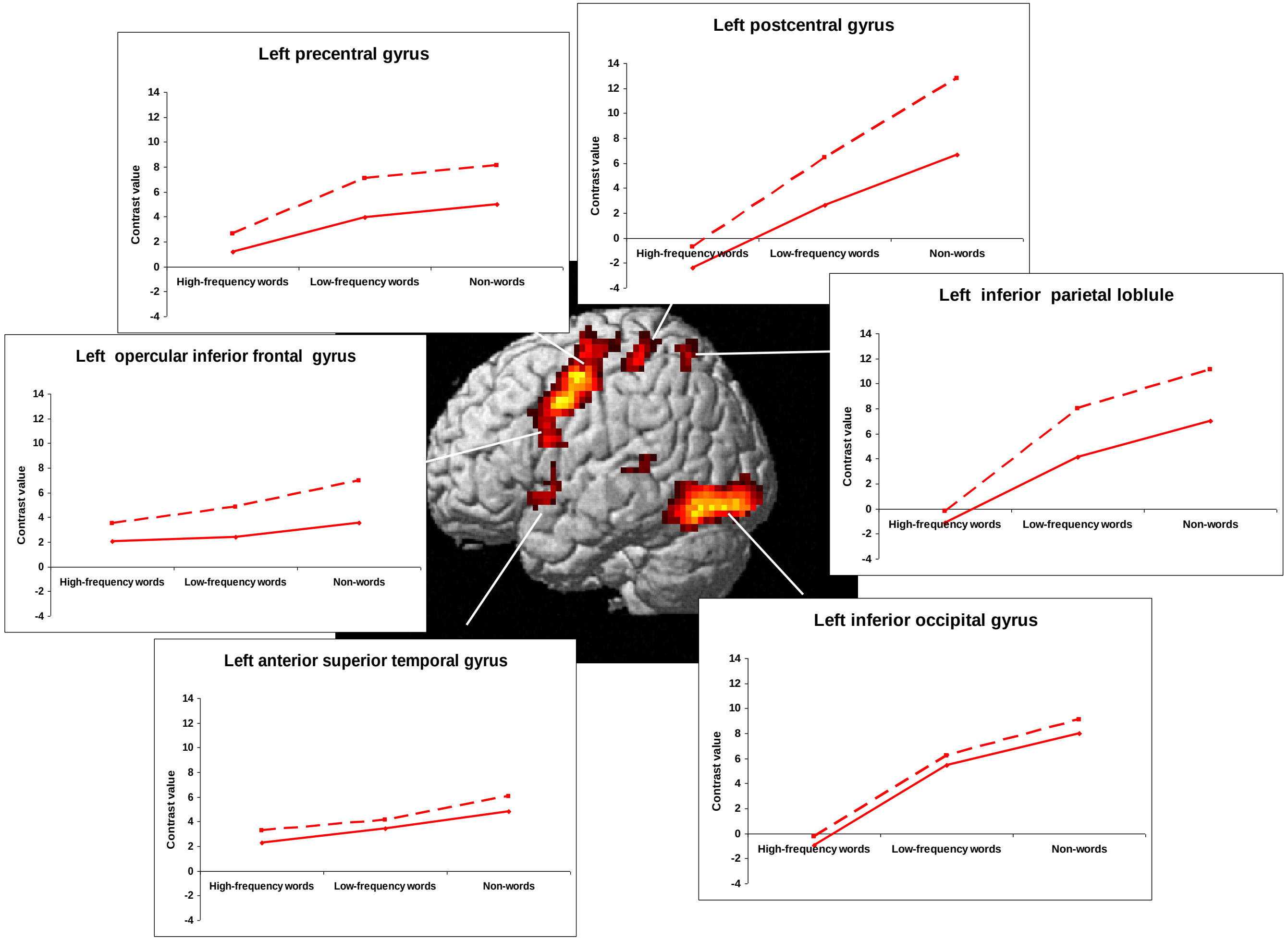

__Figure 4-22__ Schematic representation of effects found within ROIs in Spanish; continuous line represents short letter-strings; dotted line represents long letter-strings; y-axis denotes contrast values

4.3.3.3.2 Hebrew (Fig. 4-23)

Significant effects of frequency in Hebrew were found in the left inferior frontal gyrus and left inferior occipital gyrus. A significant length effect for words was detected only in the latter, though no difference was observed in the magnitude of this effect between high and low-frequency words, suggesting that frequency effects were not modulated by string length. Lexicality effects were statistically significant in all ROIs, though the patterns of interactions between lexicality and length were somewhat different. Specifically, within the left inferior frontal gyrus, lexicality effects were stronger for long relative to short letter-strings. As can be seen in Table 4-5, the length effect for non-words in this region was statistically significant. In contrast, in the left precentral gyrus and left inferior occipital gyrus negative length effects were found for non-words, and the magnitude of lexicality effects was larger for *short*, relative to long letter-strings. These patterns are reminiscent of the behavioural results in Experiment 1.

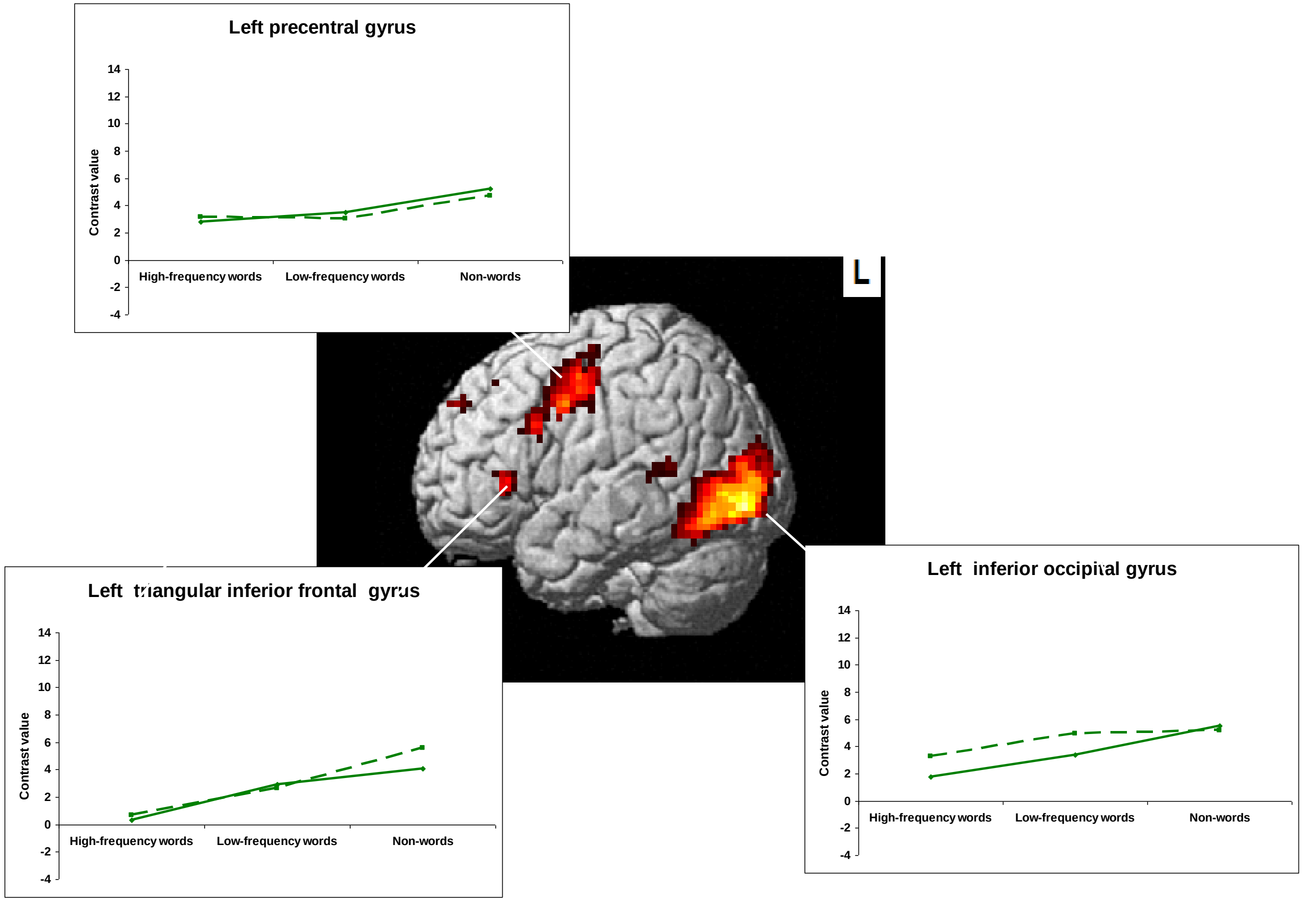

Figure 4-23 *Schematic representation of effects found within ROIs in Hebrew; continuous line represents short letter-strings; dotted line represents long letter-strings; y-axis denotes contrast values*

4.3.3.3.3 ENL (Fig. 4-24)

As shown in Table 4-5, effects of frequency were detected in all English ROIs, though the effects observed in the triangular left inferior frontal gyrus were only significant under the uncorrected threshold for short words, and approached significance under the corrected threshold for long words. The opercular IFG, the precentral gyrus and the inferior occipital gyrus produced frequency effects which were stronger for long, relative to short words, indicating a modulation of frequency effects by word-length. Word-length effects were detected within the left precentral gyrus and both opercular and triangular portions of the left IFG. As with frequency effects, the direction of length effects was parallel to the behavioural data, with stronger effects observed for low, relative to high-frequency words. In contrast, non-word length effect was only significant in the left IFG, and in the inferior occipital gyrus. Interestingly, the precentral gyrus and inferior parietal lobule were found to be more activated while participants were reading short non-words, relative to long non-words, while this negative non-word length effect was not statistically significant in the precentral gyrus (CV=0.53; t=1.17, $p_{(corrected)}$=0.54), it was strongly significant in the left inferior parietal lobule: CV =3.24; t=3.30, $p_{(corrected)}<0.003$. Lexicality effects were found in all ROIs, though the direction of effects was varied. Specifically, in the left precentral gyrus lexicality effects were only significant for short letter-strings, and similar to the pattern seen in Hebrew, stronger activation was found for short non-words, relative to long non-words in this region. Unlike Hebrew however, long non-words produced less activation than long low-frequency words in this region. Similarly, in the left inferior parietal lobule, though effects were significant for both short and long letter-strings, the lexicality effect was stronger for short letter-strings, since stronger activation was produced during short non-word reading, relative to long non-words. As shown in Figure 4-24, negative activation was detected in this region for short and long high-frequency words, thus producing strong frequency and lexicality effects, despite the fact that little difference was seen between long low-frequency words and long non-words. Within the left inferior frontal gyrus, stronger lexicality effects for long letter-strings were found in the opercular portion, with a marginally significant effect for short letter-strings. Within the triangular portion the effect for short letter-strings was somewhat stronger, though as seen in the figure, the pattern of increase in activation was similar to that observed in the opercular portion. Similarly, within the left inferior occipital gyrus a stronger lexicality effect was found for long, relative to short letter-strings, indicating a modulation of length effect by lexicality in this region.

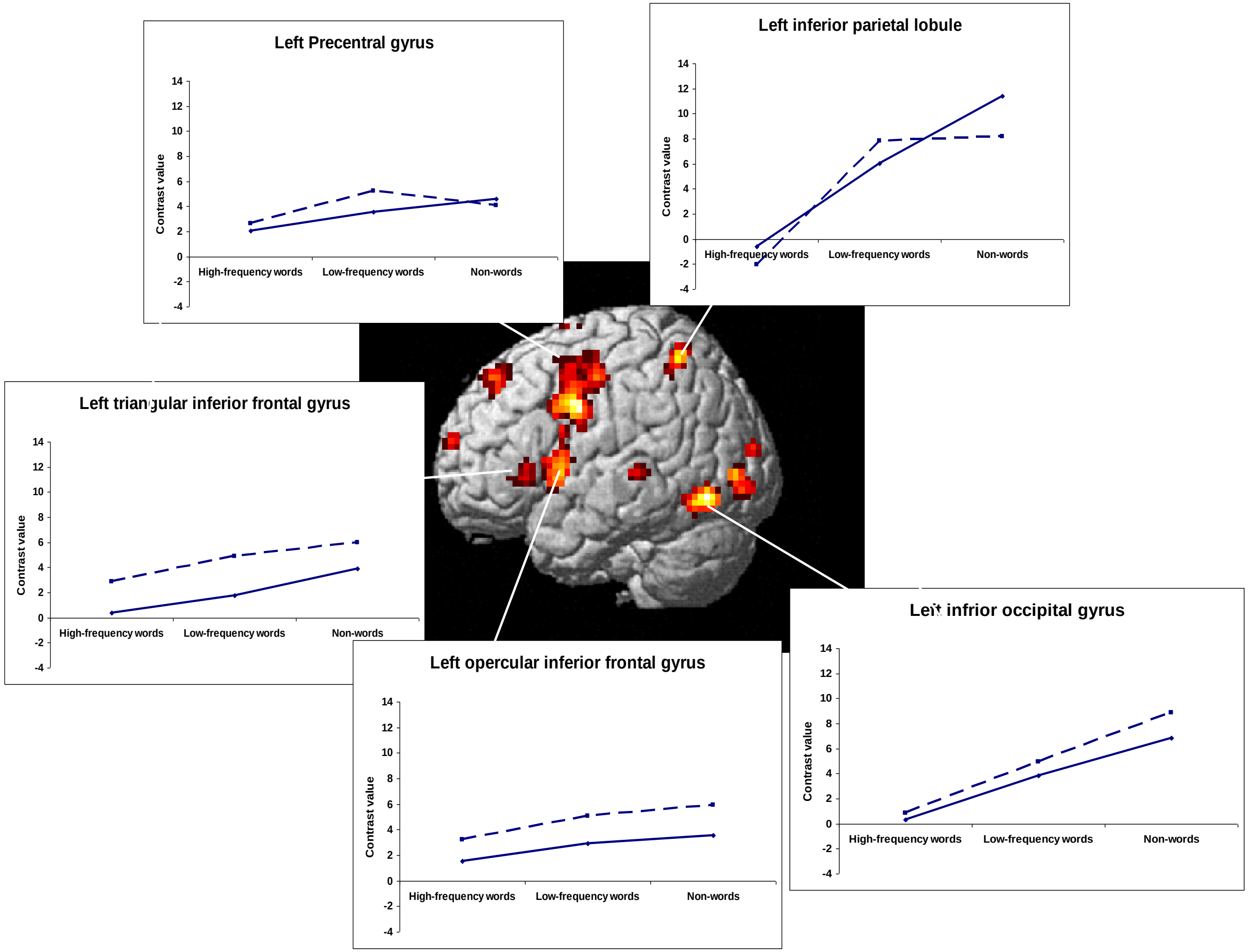

__Figure 4-24__ Schematic representation of effects found within ROIs in English; continuous line represents short letter-strings; dotted line represents long letter-strings; y-axis denotes contrast values

4.3.3.3.4 Additional regions

The right inferior occipital gyrus was commonly activated in all native languages, though as reported above, a reliable pattern of effects was not found in all three languages. As shown in the top panel of Figure 4-25, reading in Spanish led to a moderate and steady increase in activation between high-frequency words, low-frequency words and non-words, with a consistently stronger activation seen for long letter strings relative to short letter-strings. Although none of these effects reached statistical significance (all t values < 1.34, all corrected p values > 0.05), these trends suggest that contralateral cortical resources were recruited for visual analysis of written stimuli in Spanish, slightly more so for long letter-strings. The steady increase in signal intensity between the different conditions suggests that word frequency and lexicality may have influenced the activation patterns seen in this region in Spanish. Similarly in Hebrew, a moderate and steady increase was seen in signal intensity for short letter-strings between high-frequency words, low-frequency words ($t=1.7$, $p_{(corrected)}=0.24$) and non-words; $t=3.6$, $p_{(corrected)}<0.001$, while for long letter-strings the increase, which was statistically significant, was observed between high and low-frequency words only; $t=2.45$, $p_{(corrected)}<0.04$, with a slight decrease seen between low-frequency words and non-words ($t=1.59$, $p_{(corrected)}=0.29$). This pattern is markedly similar to that seen in the left inferior occipital gyrus in Hebrew, suggesting that similar to Spanish, additional contralateral resources were recruited for the visual analysis of written stimuli, and word frequency and lexicality may have played a role in the observed pattern of increase in signal strength. In contrast while reading in English as a native language, a systematic and significant increase was observed in signal intensity between long high-frequency words and long low-frequency words; $t=3.3.23$, $p_{(corrected)}<0.005$, as well as between long words and long non-words; $t=11.20$, $p_{(corrected)}<0.001$, though for short letter-strings signal intensity *decreased* in an analogous fashion (t values < 1.24, corrected p values > 0.05, parallel to the chronological progression of the experiment, rather than parallel to the behavioural data.

As shown in the middle panel of Figure 4-25, in the posterior superior temporal gyrus, reading in Spanish led to a slight increase between long high-frequency words, long low-frequency words ($t=0.99$, $p_{(corrected)}=0.80$) and a weak yet significant increase for long non-words; $t=2.71$, $p_{(corrected)}=0.03$, though for short letter-strings, there was a drop in activation intensity between high and low-frequency words ($t=1.95$, $p_{(corrected)}=0.21$), and an increase between low-frequency words and non-words; $t=2.90$, $p_{(corrected)}<0.02$. In contrast, reading in Hebrew produced an activation pattern which indicates that within this region frequency and lexicality might have played a role in the increase seen between the conditions, with stronger activation seen for long, relative to short words, and an increase in signal intensity between high and low-frequency words, and between low-frequency words and non-words, which was stronger for short, relative to long letter-strings, though these differences were not statistically significant (t values < 2.01, corrected p values > 0.05).

In the superior middle temporal gyrus, exclusively activated in English, exposure to short high-frequency words led to negative activation, with a considerable increase in activation for short low-frequency words; $t=7.17$, $p_{(corrected)}<0.001$, and a slight decrease for short non-words ($t=1.13$, $p_{(corrected)}=0.71$). Long letter-strings led to a similar, though more moderate pattern, whereby strong activation was observed for high-frequency words, with a significant increase for low-frequency words; $t=2.16$, $p_{(corrected)}<0.007$, and a moderate decrease in signal intensity for long non-words ($t=0.26$, $p_{(corrected)}=0.98$).

Perhaps the most interesting pattern of non-reliable effects was found in the medial frontal gyrus. As shown in the bottom panel of Figure 4-25, reading in Spanish yielded a pattern of change in signal intensity which was entirely consistent with the chronological progression of the experiment, and entirely inconsistent with the behavioural data. Specifically, strong activation was found in this region while participants were reading short high-frequency words, a steep drop in signal intensity was found for short low-frequency words; $t=6.02$, $p_{(corrected)}<0.001$, and a further moderate drop was seen for short non-words; $t=2.71$, $p_{(corrected)}<0.03$. For long letter-strings the pattern was parallel, with somewhat weaker activation seen throughout, relative to short letter-strings. In contrast, reading in Hebrew led to a pattern of activation which was reminiscent of the behavioural data seen in *Spanish*, with little difference in signal intensity between short high and low-frequency words ($t=0.12$, $p_{(corrected)}=0.98$), but a moderate increase between long high and low-frequency words ($t=0.07$, $p_{(corrected)}=0.66$), and a steep increase between low-frequency words and non-words, more so for long letter-strings; $t=4.37$, $p_{(corrected)}<0.001$, than for short ones; $t=3.14$, $p_{(corrected)}<0.005$. As can be seen in Figure 4-24, reading in English as a native language, similar to Spanish, led to strong activation during exposure to short high-frequency words, with a steep drop observed for short low-frequency words; t=9.9, $p_{(corrected)}<0.001$. Activation in this region during exposure to long high-frequency words was weaker relative to short high-frequency words; t=5.66, $p_{(corrected)}<0.001$, and dropped following exposure to low-frequency words; t=3.84, $p_{(corrected)}<0.001$, to yield an identical signal to that seen for short low-frequency words. Interestingly, during exposure to non-words, activation strongly increased from low-frequency words, particularly for long; t=3.99, $p_{(corrected)}<0.001$, relative to short non-words; t=2.60, $p_{(corrected)}<0.05$, yielding a pattern similar to that seen in Hebrew within this region.

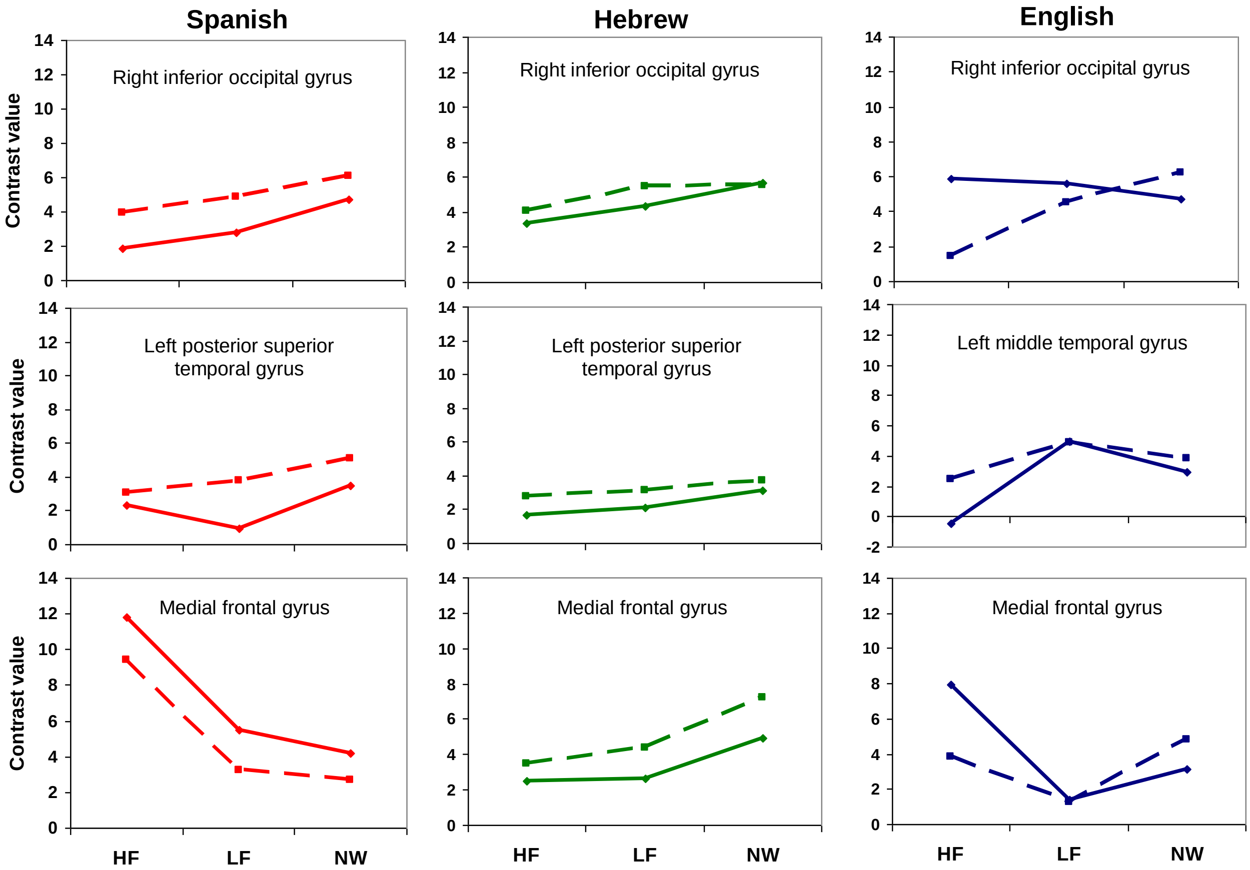

Figure 4-25 *Activation patterns found in the native languages within right inferior occipital gyrus (top panel), left posterior superior temporal gyrus (middle panel) and medial frontal gyrus (bottom panel)*
Continuous line represents short letter-strings; dotted line represents long letter-strings.

Abbreviations: HF=high-frequency words; LF=low-frequency words; NW=non-words

4.3.3.4 Effects of frequency, length and lexicality in ESL

Reliable effects of frequency, length and lexicality for both bilingual groups were found in 8 regions; these were the left precentral gyrus, left opercular inferior frontal gyrus, left inferior parietal lobule, left postcentral gyrus, left inferior occipital gyrus, right posterior middle temporal gyrus, right middle occipital gyrus, and right fusiform gyrus. The patterns of effects of frequency, length and lexicality within these regions are summarised in Table 4-6, illustrated in Figure 4-26 and described below.

4.3.3.4.1 Precentral and inferior frontal gyri

The left precentral gyrus was more strongly activated in Spanish than in ESL by the Spanish-English bilinguals, and in turn, more strongly activated in ESL than in Hebrew by Hebrew-English bilinguals. Interestingly, in the Spanish bilinguals, reading in ESL led to significant effects of frequency, length and lexicality, though very little difference was seen in the magnitude of length effects between high-frequency words, low-frequency words and non-words. In this region therefore, frequency effect was not modulated by length, and the latter was not modulated by lexicality. In contrast, the Hebrew bilinguals showed no frequency effects for short words in this region, and strong lexicality effects for short letter-strings, while an opposite pattern was seen for long letter-strings, with a strong frequency effect and a non-significant lexicality effect. Concordantly, the length effect was strong for high-frequency words and stronger yet for low-frequency words, but absent for non-words. In this group therefore, frequency effect was strongly modulated by length, but the latter was not modulated by lexicality.

Table 4-6 *Effects of frequency, length and lexicality found within ROIs in ESL by bilinguals*

		Spanish-English bilinguals				**Hebrew-English bilinguals**			
		CV	t	p (uncorrected)	p (corrected)	CV	t	p (uncorrected)	p (corrected)
Left precentral gyrus									
Frequency effects (low – high)	Short words	**1.50**	**3.94**	**<0.001**	**<0.001**	-0.13	-0.29	0.61	0.99
	Long words	**0.98**	**2.58**	**0.005**	**0.04**	**1.34**	**2.96**	**0.001**	**0.01**
Length effects (long – short)	High-frequency words	**1.62**	**4.24**	**<0.001**	**<0.001**	**1.73**	**3.80**	**<0.001**	**<0.001**
	Low-frequency words	**1.10**	**2.89**	**0.002**	**0.02**	**3.20**	**7.07**	**<0.001**	**<0.001**
	Non-words	**1.34**	**3.54**	**<0.001**	**0.002**	0.16	0.34	0.38	0.99
Lexicality effects (nw – wrds)	Short letter-strings	**3.58**	**5.41**	**<0.001**	**<0.001**	**5.28**	**6.72**	**<0.001**	**<0.001**
	Long letter-strings	**3.55**	**5.37**	**<0.001**	**<0.001**	0.69	0.88	0.19	0.81
Left inferior frontal gyrus									
Frequency effects (low – high)	Short words	**4.31**	**5.80**	**<0.001**	**<0.001**	**2.14**	**3.34**	**<0.001**	**<0.001**
	Long words	**2.24**	**3.01**	**0.001**	**0.01**	0.49	0.76	0.22	0.87
Length effects (long – short)	High-frequency words	**4.00**	**5.40**	**<0.001**	**<0.001**	**5.09**	**7.96**	**<0.001**	**<0.001**
	Low-frequency words	**1.94**	**2.62**	**0.004**	**0.03**	**3.44**	**5.39**	**<0.001**	**<0.001**
	Non-words	**3.61**	**4.88**	**<0.001**	**<0.001**	**2.30**	**3.56**	**<0.001**	**0.001**
Lexicality effects (nw – wrds)	Short letter-strings	**10.93**	**8.50**	**<0.001**	**<0.001**	**4.69**	**4.23**	**<0.001**	**<0.001**
	Long letter-strings	**12.22**	**9.51**	**<0.001**	**<0.001**	0.75	0.67	0.25	0.90
Left inferior parietal lobule									
Frequency effects (low – high)	Short words	**3.98**	**5.09**	**<0.001**	**<0.001**	**4.91**	**4.73**	**<0.001**	**<0.001**
	Long words	**6.42**	**8.19**	**<0.001**	**<0.001**	2.2	2.12	0.02	0.13
Length effects (long – short)	High-frequency words	**3.24**	**4.13**	**<0.001**	**<0.001**	**3.4**	**3.27**	**0.001**	**0.004**
	Low-frequency words	**5.66**	**7.27**	**<0.001**	**<0.001**	0.69	0.66	0.25	0.82
	Non-words	**2.88**	**3.68**	**<0.001**	**<0.001**	-2.75	-2.66	0.99	1.00
Lexicality effects (nw – wrds)	Short letter-strings	**12.51**	**9.21**	**<0.001**	**<0.001**	14.08	7.83	**<0.001**	**<0.001**
	Long letter-strings	**9.36**	**6.90**	**<0.001**	**<0.001**	**4.5**	**2.5**	**0.006**	**0.05**
Left postcentral gyrus									
Frequency effects (low – high)	Short words	**3.00**	**3.23**	**<0.001**	**0.006**	-0.03	-0.03	0.49	0.99
	Long words	**4.91**	**5.29**	**<0.001**	**<0.001**	**2.54**	**2.68**	**0.003**	**0.03**
Length effects (long – short)	High-frequency words	2.32	2.49	0.006	0.06	**3.56**	**3.76**	**<0.001**	**0.001**
	Low-frequency words	**4.23**	**4.58**	**<0.001**	**<0.001**	**6.07**	**6.42**	**<0.001**	**<0.001**
	Non-words	1.18	1.28	0.0	0.45	1.52	1.58	0.06	0.29
Lexicality effects (nw – wrds)	Short letter-strings	**11.35**	**7.05**	**<0.001**	**<0.001**	**12.85**	**7.83**	**<0.001**	**<0.001**
	Long letter-strings	**7.16**	**4.45**	**<0.001**	**<0.001**	**6.25**	**3.80**	**<0.001**	**<0.001**

Figures in bold highlight statistically significant effects

***Table 4-6** continued*

		Spanish-English bilinguals				Hebrew-English bilinguals			
		CV	t	P (uncorrected)	p (corrected)	CV	t	p (uncorrected)	p (corrected)
Left middle / inferior occipital gyrus / fusiform gyrus									
Frequency effects (low – high)	Short words	**2.86**	**5.76**	**<0.001**	**<0.001**	**1.97**	**4.88**	**<0.001**	**<0.001**
	Long words	**4.07**	**8.19**	**<0.001**	**<0.001**	**1.90**	**4.71**	**<0.001**	**<0.001**
Length effects (long – short)	High-frequency words	0.77	1.56	0.06	0.30	**1.18**	**2.95**	**0.002**	**0.01**
	Low-frequency words	**1.98**	**4.01**	**<0.001**	**<0.001**	**1.12**	**2.78**	**0.002**	**0.01**
	Non-words	0.67	1.36	0.09	0.48	0.06	0.12	0.42	0.99
Lexicality effects (nw – wrds)	Short letter-strings	**9.41**	**10.93**	**<0.001**	**<0.001**	**7.02**	**10.05**	**<0.001**	**<0.001**
	Long letter-strings	**7.99**	**9.29**	**<0.001**	**<0.001**	**4.83**	**6.90**	**<0.001**	**<0.001**
Right middle occipital gyrus									
Frequency effects (low – high)	Short words	1.39	1.91	0.03	0.23	1.53	2.00	0.02	0.17
	Long words	**2.52**	**3.46**	**<0.001**	**0.003**	**3.27**	**4.29**	**<0.001**	**<0.001**
Length effects (long – short)	High-frequency words	**3.05**	**4.18**	**<0.001**	**<0.001**	0.82	1.06	0.14	0.59
	Low-frequency words	**4.18**	**5.75**	**<0.001**	**<0.001**	**2.56**	**3.37**	**<0.001**	**0.003**
	Non-words	0.47	0.65	0.27	0.85	0.05	0.04	0.51	0.99
Lexicality effects (nw – wrds)	Short letter-strings	**9.46**	**7.47**	**<0.001**	**<0.001**	**10.73**	**8.12**	**<0.001**	**<0.001**
	Long letter-strings	**3.17**	**2.51**	**0.006**	**0.05**	**7.45**	**5.62**	**<0.001**	**<0.001**
Right fusiform gyrus									
Frequency effects (low – high)	Short words	**1.67**	**2.60**	**0.005**	**0.04**	-0.78	-1.05	0.85	1.00
	Long words	**2.92**	**4.54**	**<0.001**	**<0.001**	1.64	2.20	0.01	0.12
Length effects (long – short)	High-frequency words	**3.31**	**5.16**	**<0.001**	**<0.001**	**3.02**	**4.05**	**<0.001**	**<0.001**
	Low-frequency words	**4.55**	**7.13**	**<0.001**	**<0.001**	**5.44**	**7.32**	**<0.001**	**<0.001**
	Non-words	**1.55**	**2.42**	**0.008**	**0.05**	**5.12**	**6.85**	**<0.001**	**<0.001**
Lexicality effects (nw – wrds)	Short letter-strings	**9.94**	**8.92**	**<0.001**	**<0.001**	**4.05**	**3.14**	**<0.001**	**0.007**
	Long letter-strings	**5.17**	**4.65**	**<0.001**	**<0.001**	**5.83**	**4.51**	**<0.001**	**<0.001**
Right posterior middle temporal gyrus									
Frequency effects (low – high)	Short words	**3.01**	**2.53**	**0.006**	**0.05**	-0.33	-0.40	0.65	0.99
	Long words	2.42	2.04	0.02	0.17	0.56	0.68	0.25	0.89
Length effects (long – short)	High-frequency words	**7.17**	**6.03**	**<0.001**	**<0.001**	**3.16**	**3.78**	**<0.001**	**0.001**
	Low-frequency words	**6.58**	**5.57**	**<0.001**	**<0.001**	**4.06**	**4.88**	**<0.001**	**<0.001**
	Non-words	**4.32**	**3.64**	**<0.001**	**<0.001**	**3.17**	**3.78**	**<0.001**	**0.001**
Lexicality effects (nw – wrds)	Short letter-strings	**18.10**	**8.78**	**<0.001**	**<0.001**	**4.48**	**3.10**	**0.001**	**0.008**
	Long letter-strings	**13.01**	**6.32**	**<0.001**	**<0.001**	**3.60**	**2.48**	**0.007**	**0.05**

Figures in bold highlight statistically significant effects

In the left opercular inferior frontal gyrus, Spanish-English bilinguals showed greater activation in the native language, relative to ESL. In this group, negative activation was found for high-frequency short words, which resulted in a strong length effect for high-frequency words. This effect diminished considerably for low-frequency words, and increased for non-words. In this group therefore, the frequency by length interaction was negative, whereas the length by lexicality interaction was positive. In contrast, the Hebrew-English bilinguals, who showed greater activation in ESL relative to their native language, showed strong frequency and lexicality effects for short letter-stings, and an almost flat pattern for long letter-strings, resulting in strong length effect for high-frequency words, a somewhat weaker effect for low-frequency words, and weaker yet for non-words. These findings indicate that this region was strongly activated during exposure to long letter-strings, irrespective of frequency and lexicality, whereas during exposure to short letter-strings activation was considerably weaker, though it increased systematically as frequency decreased.

4.3.3.4.2 Parietal regions

In the parietal cortex, Spanish-English bilinguals showed similar patterns in both ROIs, both of which were more strongly activated while reading in Spanish relative to ESL. In both IPL and postcentral gyrus, these readers showed little or no activation for short high-frequency words, a strong increase in activation for low-frequency words, more so for long words i.e. positive frequency by length interaction, and strong lexicality effects, particularly for short letter-strings, i.e. a negative length by lexicality interaction. In contrast, the Hebrew-English bilinguals, who did not activate the parietal cortex in their native language, showed a systematic increase in signal intensity during exposure to long letter-strings in ESL in both parietal regions, but the patterns elicited during exposure to short letter-strings were markedly different. In the postcentral gyrus very little activation occurred during high and low-frequency word reading, with no difference in signal intensity between the two word-types, whereas short non-word reading led to a strong increase in activation. Length effects in this region were therefore strong for high-frequency words, stronger yet for low-frequency words, but considerably weaker for non-words. In contrast, in the inferior parietal lobule a linear increase in signal intensity was observed between high-frequency words, low-frequency words and non-words, resulting in a blunt negative frequency by length interaction, and a negative length effect for non-words.

4.3.3.4.3 Occipto-temporal regions

Both bilingual groups showed stronger activation in their native languages relative to ESL in the left occipito-temporal cortex. Within this region strong effects of frequency and lexicality were found for both groups, though while Hebrew-English bilinguals showed no difference in magnitude of frequency effect between short and long words, the Spanish-English bilinguals showed stronger frequency effect for long, relative to short words, indicating a positive frequency by length interaction in this group. In contrast, both bilingual groups showed stronger lexicality effects for short, relative to long letter-strings, resulting in a negative interaction between lexicality and length, and a non-significant length effect for non-words.

In the right occipito-temporal cortex, the Spanish-English bilinguals showed similar patterns of effects in both regions; moderate frequency effects and strong lexicality effects for short letter-strings, with little or no activation for short high-frequency words, a moderate increase for short low-frequency words and a considerable increase for short non-words. Concurrently, for long letter-strings a strong frequency effect and a moderate lexicality effect were observed, with strong activation for long high-frequency words, a considerable increase for long low-frequency words, and a moderate increase for long non-words. Word-length effects in both occipital regions were considerably strong, whereas non-word length effects were relatively weak.

The Hebrew-English bilinguals showed different activation patterns in the two occipital regions. In the right middle occipital gyrus, which was more strongly activated in ESL relative to Hebrew, the pattern was similar to that observed in the Spanish-English bilinguals, with moderate frequency effect for short words and strong lexicality effect for short letter-strings. At the same time, for long letter-strings frequency effect was also considerably strong, indicating a positive frequency by length interaction and a negative length by lexicality interaction. In contrast, within the right fusiform gyrus, which was more strongly activated in the native language, relative to ESL, a negative frequency effect was seen for short words, and a positive, though non-significant effect was seen for long words. Length effects were considerably strong, particularly for low-frequency words, thus producing a positive frequency by length interaction. Similarly, lexicality effects in this region were somewhat stronger for long, relative to short letter-strings, though the magnitude of increase in signal intensity between short low-frequency words and short non-words did not differ from that seen between long low-frequency and long non-words, due to the negative frequency effect seen in short words.

4.3.3.4.4 Right middle temporal gyrus

The right middle temporal gyrus was activated in both bilingual groups exclusively while reading in ESL. Within this region, Hebrew-English bilinguals showed an identical pattern to that observed within the right fusiform gyrus, whereas the Spanish-English bilinguals showed a somewhat different pattern, whereby signal intensity increased systematically between high-frequency words, low-frequency words and non-words, more so for short, relative to long letter-strings. Despite a negative activation for short high-frequency words, and null activation for short low-frequency words, frequency effect for short words was statistically significant, whereas that for long words did not reach statistical significance under the corrected threshold. Similarly, length effects were stronger for high-frequency words relative to low-frequency words, and lexicality effects were stronger for short letter-strings, relative to long letter-strings.

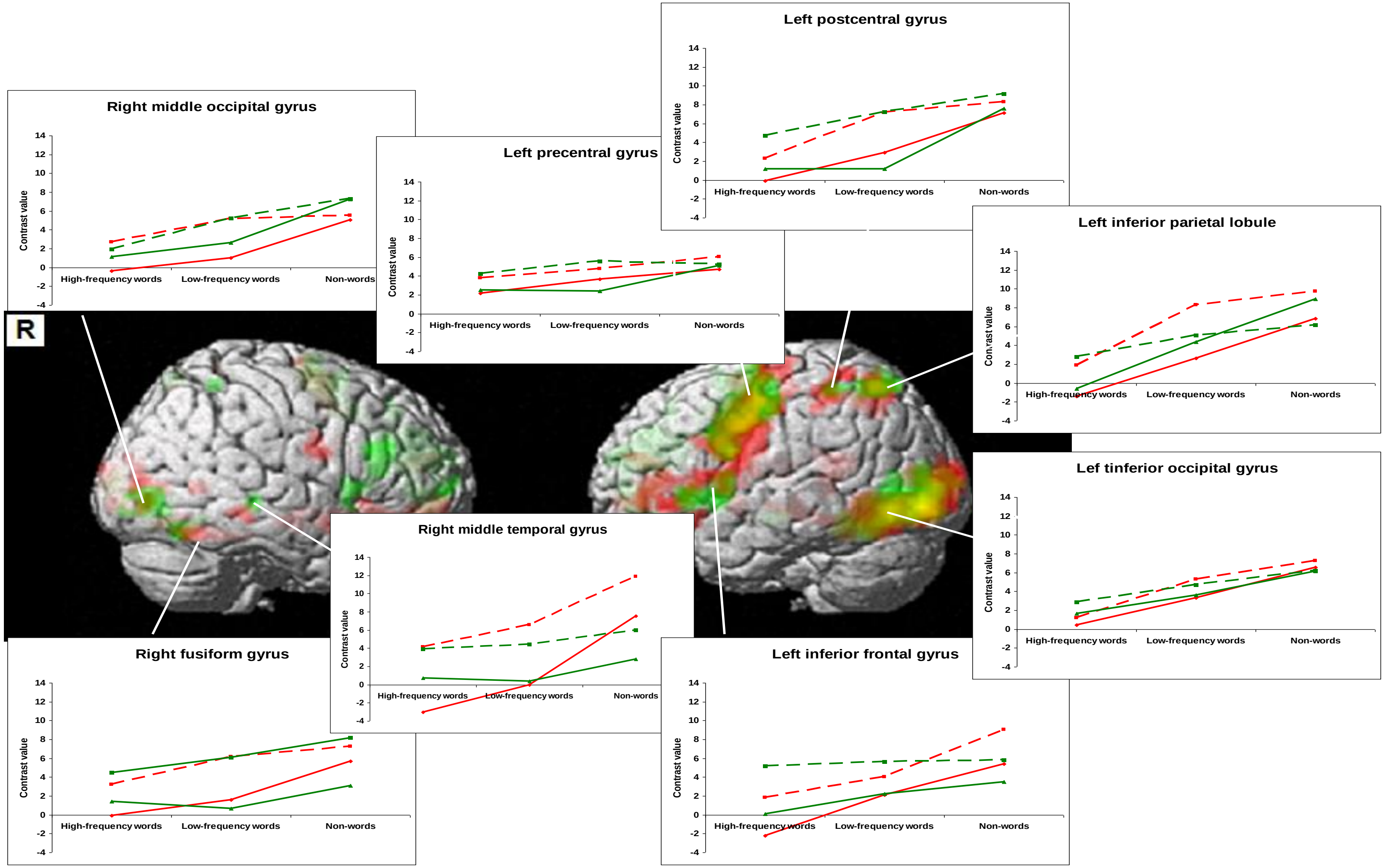

Figure 4-26 *Schematic representation of effects found within ROIs in ESL by Spanish-English (represented in red) and Hebrew-English (represented in green) bilinguals; continuous line represents short letter-strings; dotted line represents long letter-strings; y-axis denotes contrast values*

4.3.3.4.5 Medial frontal gyrus

An additional region, commonly activated by the two groups while reading in ESL was the posterior medial frontal gyrus. This region did not give rise to reliable frequency, length and lexicality effects in either group of bilinguals, though as noted earlier, significantly stronger activation was found in this region in ESL relative to both native languages. As shown in Figure 4-27, both groups showed a similar trend in the direction of change in signal intensity, which was consistent with the chronological progression of the experiment. Spanish-English bilinguals showed strong activation for high-frequency words, which gradually decreased as the experiment progressed. For short words the decrease was relatively moderate and was not statistically significant ($t=1.40$, $p_{(corrected)}=0.53$), whereas for long words the decrease was steep; $t=4.10$, $p_{(corrected)}<0.001$, and stronger yet for non-words, more so for long; $t=7.46$ $p_{(corrected)}<0.001$ than for short letter-strings; $t=5.51$, $p_{(corrected)}<0.001$. The Hebrew-English bilinguals however, showed overall weaker activation in the posterior medial frontal gyrus, and concordantly a moderate decrease between the first and last experimental blocks (t values < 0.76, corrected p values > 0.05). Interestingly, greater activation was found for long, relative to short high-frequency words; $t=2.43$, $p_{(corrected)}<0.04$, a difference which decreased as the experiment progressed.

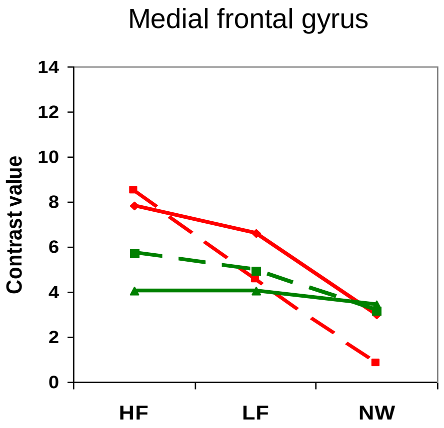

Figure 4-27 *Activation patterns found in the medial frontal gyrus while reading ESL by Spanish-English (red) and Hebrew-English (green) bilinguals;*
Continuous line represents short letter-strings; dotted line represents long letter-strings

4.3.4 Discussion

The present experiment visualised the neural correlates of processing strategies employed for reading Spanish, English and Hebrew as native languages, as well as those employed for reading in ESL by bilinguals of Spanish and English, and Hebrew and English. The results will be discussed in several sections. First, the observed patterns of activation in the native languages are discussed by initially focussing on the anatomical regions found to be activated in response to reading in each language, followed by an interpretation of the observed effects of frequency, length and lexicality within regions of interest. Then, the discussion turns to the patterns of activation observed while bilinguals were reading in ESL. Within this section differences between reading in ESL and each native language are highlighted in terms of language proficiency effects and orthographic transparency effects, leading to a discussion of the differences and similarities between the two bilingual groups.

4.3.4.1 Reading in the native languages

As outlined in the Literature Review, behavioural and neuroimaging studies examining the processes involved in reading have highlighted a distinction between orthographic, sublexical / phonological and lexical / semantic processing (e.g. Coltheart & Rastle, 1994; Seidenberg & McClelland, 1989), and have shown some distinction within the neural substrates mediating these processes (Pugh et al, 1996; Fiez et al, 1999; McDermott et al, 2003; Wydell et al, 2003; Joubert et al, 2004; Booth et al, 2006; Bick et al, 2008). Moreover, cross-language studies have indicated that reading in different languages involves different levels of reliance on lexical and sublexical processing, influenced by their orthographic properties (e.g. Frost, Katz & Bentin, 1987), which may yield different patterns of neural activation (e.g. Paulesu et al, 2000). Accordingly, the behavioural experiments described in the previous chapter showed that reading in Spanish, English and Hebrew entailed different reading strategies, in keeping with their graded levels of orthographic transparency.

Results of the present fMRI experiment confirmed this assertion by showing that while all three native languages activated largely overlapping regions within left precentral and middle frontal gyri, bilateral inferior and middle extrastriate occipital and occipito-temporal cortex, as well as medial frontal gyrus, some preferential activation was detected within areas associated with distinct types of processing. Specifically, reading in Hebrew was associated with activation within the anterior (triangular) portion of the inferior frontal gyrus, whereas reading in Spanish led to activation within more posterior (opercular) regions, and reading in English as a native language activated both areas within the gyrus. Previous monolingual studies have shown that while the anterior portion of the IFG was associated primarily with lexical / semantic processing, activation in more posterior areas of the gyrus reflected sublexical / phonological processing (Fiez et al, 1999; Poldrack et al, 1999; McDermott et al, 2003; Joubert et al, 2004; Booth et al, 2006; Bick et al, 2008). In addition, reading in Spanish was exclusively associated with activation in the postcentral gyrus, previously implicated in phonological processing (McDermott et al, 2003; Booth et al, 2006). Furthermore, as observed in Experiment 3, Spanish and English were associated with activation in the left inferior parietal lobule, while no activation was detected in this region in Hebrew. Given that this region has been previously associated with processes reflecting grapheme-to-phoneme conversion (Poldrack et al, 1999; McDermott et al, 2003; Joubert et al, 2004; Booth et al, 2006), this finding indicates that readers of Spanish and English were prone to rely on this strategy, particularly when presented with low-frequency words and non-words, as seen by the systematic increase in BOLD signal intensity between high-frequency words, low-frequency words and non-words. In contrast, readers of Hebrew showed no activation within this region, since grapheme-to-phoneme conversion would not be beneficial to reading in this language due to the absence of written vowels. Moreover, English and Hebrew were associated with activation in the right superior and middle frontal gyrus, which have been previously implicated in complex orthographic processing of logographic scripts (e.g. Liu & Perfetti, 2003; Valaki et al, 2004; Nakamura, Oga, Okada et al, 2005), as well as contributing to semantic processing in English (e.g. Poldrack et al, 1999; Strange et al, 2000). Finally, bilateral activation within the extrastriate occipital and occipito-temporal cortex was observed in all three native languages, all of which showed stronger and more extensive activation in the left relative to the right hemisphere. However, the extent to which the right occipito-temporal cortex was activated varied between the languages, with spatially extensive activation seen in Hebrew, moderate activation seen in English, and very little activation seen in Spanish. In alphabetic languages, activation within homologous language processing regions in the right hemisphere has been previously associated with coarse semantic coding (e.g. Chiarello et al, 1990; Lavidor & Ellis, 2002), therefore the gradual manner in which the extent of right occipital cortex activation varied in the different languages could be viewed as parallel to their position along the orthographic transparency continuum.

These observations therefore indicate that reading in Spanish was associated with some preferential activation in regions reflecting predominant reliance on phonological assembly, reading in Hebrew yielded activation in regions predominantly associated with lexical and semantic processing, whereas reading in English led to activation within regions associated with both types of processing. Importantly, visualising the effects of frequency, length and lexicality within regions of interest provided further support for this view. The following three subsections discuss the observations of effects within these regions.

4.3.4.1.1 Effects of frequency, length and lexicality within frontal and parietal regions

As expected, Spanish readers showed consistent and robust length effects in frontal and parietal ROIs as well as positive interactions between frequency and length, and lexicality and length. Native English readers showed overall weaker effects of word length, and weak interactions between frequency and length effects, observed only within the precentral gyrus and inferior parietal lobule. In the inferior frontal cortex length effects were prominent, though these did not modulate the effects of frequency and were not modulated by lexicality. By contrast, Hebrew readers exhibited no word-length effects in frontal ROIs, though frequency and lexicality effects were weak, but significant, particularly within the triangular IFG. Interestingly, a weak length effect was detected in this region while Hebrew readers were exposed to non-words. This may reflect traces of an attempt to sequentially assemble these letter-strings, since long Hebrew words may sometimes convey some phonemic information due to the presence of mothers of reading.

A region which was not expected to yield reliable effects but nevertheless showed an interesting pattern of change in signal intensity was the medial frontal gyrus. This region has been repeatedly shown to be implicated in processes of working memory and attention (reviewed by Price, 2000; Fernandez-Duque & Posner, 2001). In the native Spanish speakers, the systematic decrease in signal intensity, parallel to the progression of the experiment suggests that these readers were recruiting attentional resources at the early stages of the experiment, which gradually diminished with habituation to the environment and task (Henson, Shallice & Dolan, 2000, Pilgrim, Fadili, Fletcher & Tyler, 2002). In contrast, the Hebrew readers showed a systematic increase in signal intensity throughout the experiment, suggesting that in this language, more attentional resources were required for processing written stimuli of increasing difficulty. Interestingly, the native English speakers showed a decrease in activation between exposure to high-frequency words and low-frequency words, and an increase during exposure to non-words, suggesting that while habituation occurred for word stimuli, the transition to non-words exerted a greater demand on attentional processing. Therefore, the differences in the patterns of activation in the medial frontal gyrus between the three languages can also be placed in parallel to the position of these languages along the orthographic transparency continuum.

4.3.4.1.2 Temporal regions

Some controversy exists in the current literature with regards to the role of the posterior superior temporal cortex in visual word recognition. Given that this region was repeatedly shown to mediate spoken language comprehension, its role in reading has often been associated with phonological processing (e.g. Fiez et al, 1999; Joubert et al, 2004), and indeed, several studies have observed stronger activation in this region during exposure to transparent languages such as Italian (Paulesu et al, 2000), Dutch (Vingerhoets et al, 2003) and Spanish (Meschyan & Hernandez, 2005). However, others have provided evidence suggesting that this region may be involved in semantic processing (e.g. McDermott, et al, 2003, Bick et al, 2008). In their MEG study with Finnish monolinguals, Wydell et al (2003) suggested that the left superior temporal cortex may in fact mediate both types of processing, since a combined length and lexicality effect was detected in this region during a relatively late course of activation.

In the present experiment, activation in the left posterior STG was observed in Spanish and Hebrew, but the patterns of frequency, length and lexicality effects were not entirely consistent, and therefore difficult to interpret. In Hebrew this region may have been involved in phonological processing, as seen by the moderate and steady increase in activation between high-frequency words, low-frequency words and non-words, coupled by somewhat stronger activation associated with long letter-strings. In Spanish the pattern may reflect a combination of linguistic effects coupled by task effects, whereby upon initial exposure to short high-frequency words this area was engaged, possibly in phonological analysis, followed by temporary habituation, similar to that observed in the medial frontal cortex, since short low-frequency words may not require a great deal of phonological analysis (as seen in the RT pattern in Experiment 1). However, subsequent exposure to long low-frequency words may have re-engaged this region, leading to a systematic increase in activation as a function of frequency and length.

Interestingly, reading in English was not associated with activation in the posterior STG; instead, the middle temporal gyrus was activated specifically in English, though unlike in Experiment 3, this pattern was observed exclusively in ENL. The discrepancy between the two experiments may have stemmed as a result of individual differences, whereby the two bilinguals in Experiment 3 showed activation within this region while reading in ESL, whereas the majority of bilinguals in the present experiment did not. This highlights the importance of the use of multiple subjects in neuroimaging experiments, where due to practical constraints, many studies, particularly those recruiting multilinguals, have relied on relatively small sample sizes (6 participants or less; e.g. Yetkin et al, 1996; Hernandez et al 2001; Briellmann et al, 2004; see Thirion, Pinel, Mériaux, Roche, Dehaene & Poline, 2007 for a discussion). In the present experiment, the observed patterns of signal change in the different ENL conditions indicates that this region was engaged during exposure to long high-frequency words, but not short high-frequency words. Similarly, exposure to low-frequency words led to an increase in activation in this region regardless of length, whereas processing resources for non-words may have been diverted elsewhere, e.g. medial and lateral frontal regions. These observations are in keeping with previous findings implicating the middle temporal gyrus in semantic processing specifically in English (Pugh et al, 1996; Paulesu et al, 2000; McDermott et al, 2003).

An additional temporal region found to be activated in the present experiment was the anterior portion of the left STG. This region was specifically activated in Spanish, and the observed pattern of frequency, length and lexicality effects were also suggestive of semantic processing, as evidenced by a systematic increase in activation between high-frequency words, low-frequency words and non-words, with minimal length effects. Indeed, this region has been previously associated with semantic processing. For example, in a PET study investigating the neural correlates of semantic priming using a lexical decision task, Mummery, Shallice and Price (1999) found that relative to letter decision (baseline task), the lexical decision task elicited activation within the left anterior temporal lobe. Across scans, the proportion of related prime-target pairs varied between 0 to 100%. Interestingly, activation in this region systematically decreased as the proportion of semantically related targets increased, except for the highest proportion of priming, where activation increased. This U-shaped function was explained in terms of automatic priming leading to a decrease in activation with task progression, which attenuates and reverses as strategic priming mechanisms[18] become involved with the increase of the proportion of semantically related targets. The authors thus concluded that whether automatic or strategic, the left anterior temporal cortex was sensitive to lexico-semantic processing. Similarly, Price and colleagues (Price, Gomo-Tempini, Graham, Biggio et al, 2003) have noted that a patient with surface dyslexia exhibited reduced activation in the left anterior superior temporal cortex compared to control subjects, implicating this region in semantic processing in regular readers. In the present experiment therefore, while activation patterns in Spanish were predominantly associated with phonological processing, there was clear evidence for some semantic processing occurring in this transparent language. These observations are consistent with observed cases of surface dyslexia in transparent languages such as Spanish (e.g. Ruiz, Ansaldo & Lecours, 1994; Iribarren et al, 2001), and with studies showing lexical / semantic processing in languages such as Persian (Baluch & Besner, 1991) and Italian (Tabossi & Laghi, 1992). A possible explanation for the absence of activation within this region in Hebrew and English could be related to methodological constraints stemming from whole-brain analysis. Note that ROI

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[18] The terms ‘automatic’ and ‘strategic’ priming mechanism refer to the cognitive processes that lead to priming effects, whereby activation of the semantic system can occur automatically, or through strategic attentional processes (see Henson, 2003 for a review).

analysis was utilised in order to circumvent this problem, and thus detect a reliable pattern of activation in each condition within said regions. However, recall that the initial identification of ROIs was carried out by selecting regions that were activated in the Reading > Baseline condition using a whole-brain analysis. Since extensive activation related to semantic processing was reliably detected in these languages within the inferior frontal cortex, it is plausible that any activation which may have occurred within the anterior temporal cortex was relatively weak, and therefore may have gone undetected. Indeed, this still constitutes one of the strong limitations of fMRI, and is the focus of a large body of studies aimed at optimising the reliability and accuracy of hemodynamic neuroimaging methods (e.g. Erberich, Specht, Willmes, Kemeny & Reith, 2000; Swallow, Braver, Snyder, Speer & Zecks, 2003; Seghier, Friston & Price, 2007).

4.3.4.1.3 Occipito-temporal regions

In Spanish and English robust effects of frequency and lexicality were detected in the left inferior and middle occipital cortex, while length effects were virtually absent. Activation in the occipital cortex has been previously associated with low-level visual analysis upon initial exposure to printed material (Pugh et al, 1996; Wydell et al, 2003), though in the present experiment, the absence of length effects suggests that the subtraction of activation related to the reading conditions from that related to the control condition yielded mainly activation associated with linguistic processing. This finding is in keeping with previous observations attesting that regions within the left inferior occipito-temporal cortex, particularly the fusiform gyrus may be specifically involved in visual processing of word forms (Cohen et al, 2002). Concordantly, the left inferior occipito-temporal cortex has also been shown to be sensitive to frequency and lexicality effects (Fiez et al, 1999; Paulesu et al, 2000; Proverbio et al, 2008). Therefore the presently observed pattern of effects in the left occipito-temporal cortex in Spanish and English suggests that at early stages of visual word recognition, namely orthographic processing, some lexical lookup process may have been taking place, leading to a systematic increase in cerebral blood flow as a function of word-frequency. Subsequently, parietal regions were engaged in associative processes of grapheme-to-phoneme conversion of low-frequency words and non-words, giving rise to length effects in both languages, and particularly in Spanish. At the same time, the temporal cortex (middle temporal gyrus in English and anterior superior temporal gyrus in Spanish) may have been involved in lexical / semantic processing, followed by later phonological assembly and articulatory programming in the frontal cortex, in both languages.

The role of the right occipital cortex in this process was somewhat difficult to interpret since the pattern of effects was not entirely reliable. It is plausible that activation in this region in Spanish may reflect some residual low-level visual analysis despite the subtraction from the baseline condition, while in English, the reliable pattern of effects observed for long letter-strings suggests that the right middle occipital cortex was recruited in the early stages of word identification for orthographic processing coupled by some lexical lookup (e.g. Chiarello et al, 1990; Tan et al, 2001; Simon et al, 2006)

In Hebrew the observed patterns were rather different; in addition to frequency and lexicality effects, reading long words of high and low frequency induced a higher intensity of activation in the occipito-temporal cortex bilaterally, relative to short words, whereas reading non-words did not elicit any length effects in these regions. These observations can account for the increased length effect seen in the Hebrew naming latency data in Experiment 1, suggestive of a strategic dilemma faced by Hebrew readers, whereby upon initial exposure to printed letter-strings, participants attempted sequential orthographic assembly before resorting to lexical lookup. At the same time, for non-words, the increased difficulty in articulating consonant strings which have no lexical representation led to slower orthographic processing, evidenced as considerably slow RT in the behavioural experiment, which at the cortical level was manifested within the left IFG as a length effect for non-words. Importantly, in Experiment 1, where words and non-words were presented in a mixed randomised fashion, evidence for the strategic dilemma was robust. It is therefore plausible that had the present experiment been designed in an event-related manner, whereby randomised presentation of stimuli had been possible, the word-length effects seen in the occipital cortex would have been considerably stronger. This is an important consideration for future studies involving Hebrew.

Taken together, the observed patterns of activation and effects of frequency, length and lexicality suggest that reading in the three native languages was achieved via a network of shared cortical regions, while the extent to which phonological and semantic processes were engaged varied between the languages, in keeping with their position along the orthographic transparency continuum. These findings corroborate the assertion that the neural substrates involved in reading different languages are constrained by culture-specific mappings of orthography-to-phonology (Paulesu et al, 2000; Meschyan & Hernandez, 2005; Simon et al, 2006), and are in line with the currently accepted version of the Orthographic Depth Hypothesis (Katz & Frost, 1992).

4.3.4.2 Reading in ESL

Much debate exists in the literature focussed on multiple-language processing, regarding the effects of language proficiency and orthographic properties of different languages on reading strategies in the native, relative to less dominant languages. As outlined in Chapter 2, early observations of differentially manifested symptoms of aphasia in different languages had given rise to the notion that different languages may be represented by separate neural substrates (Paradis, 1977; Potzl, 1983; Kauders, 1983; Fabbro & Gran, 1997; reviewed by Fabbro, 2001), while more recent experimental studies using behavioural methods have indicated that multiple-language processing may be mediated largely by common mechanisms (e.g. Beauvillain & Grainger, 1987; Van Heuven, Dijkstra & Grainger, 1998; Jared & Kroll, 2001; Gollan, Forster & Frost, 1997; Lemhoefer, Dijkstra & Michel, 2004). Moreover, neuroimaging studies aimed at examining multiple-language representation have shown that differences between cortical regions associated with processing of different languages may arise due to inferior levels of proficiency in less dominant languages (e.g. Klein et al, 1994; Wattendorf et al, 2001; Pillai et al, 2003; Vingerhoets et al, 2003; Halsband, 2006).

In keeping with this view, the behavioural results reported in Experiment 1 showed slower naming and lower levels of accuracy in ESL relative to the native languages. Concordantly, the results of the present experiment showed marked overlap in regions activated in ESL by both bilingual groups, with ESL relative to the native languages, associated with stronger activation within the medial frontal cortex, as well as significant activation within the right precentral, inferior frontal and middle temporal gyrus, not present in Spanish and Hebrew, or indeed in English as a native language. As outlined in the Literature Review, some authors have shown that L2 may be associated with stronger right hemisphere activation, particularly in late bilinguals (Dehaene et al, 1997; Proverbio et al, 2002; Pillai et al, 2003). Since the native English monolinguals in the present experiment did not show activation in right precentral, inferior frontal or temporal regions, it is plausible that these regions were recruited while reading in ESL for additional linguistic processing resources. In addition, reading in ESL relative to Hebrew was associated with stronger activation in the right middle occipital gyrus, a region which was also activated in ESL by Spanish bilinguals, but not in Spanish, suggesting that additional processing resources for reading in the less dominant language were also recruited within this region. However, recall that reading in ENL and in Hebrew were also associated with activation within this region, and importantly, Hebrew readers showed stronger and more extensive activation than native English readers, suggesting that the right middle occipital gyrus may also be sensitive to orthographic transparency.

These findings therefore corroborate the assertion that reading in two languages largely entails a common neural network, while some differences between L1 and L2 may arise either as a result of inferior L2 proficiency, or may be related to orthographic transparency. Indeed, recent observations of differentially manifested symptoms of dyslexia in bilingual individuals have raised this notion (e.g. Wydell & Butterworth, 1999; Beland & Mimouni, 2001). Concurrently, neuroimaging studies with bilinguals have shown some distinct patterns of activation associated with reading in languages of contrasting levels of orthographic transparency (e.g. Nakada et al, 2001; Tan et al, 2001; Liu & Perfetti, 2003; Valaki et al, 2003; Ding et al, 2003; Lee, et al, 2004, Siok et al, 2006; Meschyan & Hernandez, 2005; Simon et al, 2006).

The present neuroimaging data showed that reading in Spanish relative to ESL led to stronger activation within regions implicated in phonological processing, namely left precentral gyrus, left postcentral gyrus and left inferior parietal lobule. These findings are in keeping with Meschayn and Hernandez (2005), who showed that the orthographically transparent Spanish was associated with activation in regions implicated in phonological processing to a greater extent than English. At the same time, being a less dominant language, Spanish led to stronger activation within the medial frontal cortex relative to the dominant language, English.

In the present study, the Hebrew-English bilinguals showed a similar pattern, whereby reading ESL, in this case the relatively more transparent language, was associated with activation within the postcentral gyrus and inferior parietal lobule, not present in Hebrew, and stronger activation relative to Hebrew, within the left precentral gyrus and inferior frontal gyrus. In contrast, reading in Hebrew led to stronger activation in the right fusiform gyrus. Interestingly, this region has often been referred to as the fusiform face area (FFA; Kanwisher, McDermott & Chun, 1997), since in contrast to its homologue, the visual word form area (Cohen et al 2002), this region has been repeatedly associated with object recognition, particularly faces and other objects of expertise (e.g. Gauthier & Tarr, 2002; see Palmeri & Gauthier, 2004 for a review). However, several studies focussed in visual word recognition have also observed activation in this region (e.g. Fiez et al, 1999; McDermott et al, 2003; Vingerhoets et al, 2003; Booth et al, 2006), though its role in reading has seldom been addressed. Importantly, in the present study, the same region was found to be more strongly activated in ESL by Spanish bilinguals, relative to Spanish, suggesting that it may be sensitive to orthographic transparency.

Within this framework of investigation a widely controversial issue is whether reading strategies acquired in bilinguals' native language might be transferred to reading in their second language. While some recent findings, relying on extreme ends of the orthographic transparency continuum, such as Chinese and Japanese Kanji have argued for this effect (e.g. Muljani, Koda & Moates, 1998; Wang, Koda & Perfetti, 2003), others have suggested the contrary (e.g. Akamatsu, 2002). Most recently, Lemhöfer and colleagues (Lemhöfer, Dijkstra, Schriefers, Baayen, Grainger & Switserlood, 2008) have shown that in bilinguals, native speakers of western European languages of somewhat varied levels of orthographic transparency (German, Dutch or French as L1) and English (L2), word recognition in L2 was primarily determined by within-language factors, while cross-language transference of strategy was limited.

In Experiment 1 observed patterns of naming latency indicated that the strategies employed by bilinguals of Spanish and English, and Hebrew and English for reading in their second language were not transferred from the their native languages. In fact, while the Spanish-English bilinguals showed an efficient adaptation of the reading strategy to the less transparent English, the Hebrew-English bilinguals showed a pattern which was suggestive of an exaggerated reliance on phonological recoding for reading in this relatively more transparent language. Indeed, the overlaid anatomical pattern of activation observed in each group in the present experiment showed that the Spanish bilinguals activated more anterior portions of the left inferior frontal cortex, while the Hebrew bilinguals activated more posterior portions. Moreover, the observed patterns of effects of frequency, length and lexicality and interactions within some of the commonly activated regions by the two groups further support this view.

Within the posterior medial frontal gyrus, the pattern of change in signal strength was in the same direction in both bilingual groups; consistent with the chronological progression of the experiment rather than with the naming latency data. However, while the Spanish bilinguals showed a pattern similar to that observed in their native language, indicating that attentional resources were most strongly engaged at the beginning of the experiment and gradually decreased with habituation, the observed trends in the Hebrew bilinguals were somewhat different. During exposure to short letter-strings no change was seen in signal strength between high- and low-frequency words, whereas upon exposure to non-words a weak decrease was observed, suggesting a moderate habituation. In contrast, for long letter-strings initial exposure may have required greater attentional demands as evidenced by a significant difference in signal intensity between short and long high-frequency words, which decreased with the progression of the experiment. Recall that this trend was reversed while these participants were reading in their native language, since reading in Hebrew became more laborious as frequency of items decreased. The differences between the two bilingual groups in ESL however, suggest that for the Hebrew readers, processing long letter-strings exerted a greater attentional demand relative to short letter-strings, which may account for the slower naming observed in the behavioural data.

In the opercular inferior frontal gyrus, while Spanish bilinguals showed robust frequency and lexicality effects, Hebrew bilinguals showed almost no change in the magnitude of activation between high-frequency words, low-frequency words and non-words. Instead, length effects in this region were rather robust. Since strong length effects are suggestive of phonological processing (Wydell et al, 2003), whereas a strong frequency and lexicality effects, with minimal modulation by consistency (or in this case, string-length) are suggestive of lexical processing (Fiez et al, 1999; Paulesu et al, 2000), the strong effects of frequency and lexicality in the Spanish bilinguals relative to the Hebrew bilinguals could point towards a greater reliance on lexical / semantic processing in the former group, relative to the Hebrew group. In turn, the latter group exhibited strong length effects in this region albeit moderate frequency and lexicality effects, which may point towards stronger reliance on phonological processing strategies for reading in ESL.

Similarly, within the right middle temporal gyrus, the Spanish bilinguals exhibited robust lexicality effects for short letter strings, and strong frequency and lexicality effects for long letter-strings, while in the Hebrew bilinguals these effects were moderate. Since this region was exclusively activated in ESL in both groups, a plausible interpretation of the pattern seen presently is that this region was recruited as an additional processing resource for reading in L2, particularly low-frequency long words and long non-words, and as in the left IFG, the Hebrew bilinguals may have relied on phonological processing within this region, to a greater extent than the Spanish bilinguals.

Finally, within the right fusiform gyrus, both bilingual groups showed a positive interaction between frequency and length for real words, whereas a negative lexicality by length interaction was seen in the native Spanish bilinguals. This was due to a relatively stronger lexicality effect for short, relative to long non-words in this group. In contrast, although no interaction between lexicality and length was seen for the Hebrew bilinguals, the length effect for non-words was markedly stronger relative to the Spanish bilinguals, suggesting that within this region as well, the Hebrew-English bilinguals may have relied on assembled phonology for reading in ESL to a greater extent than the Spanish-English bilinguals.

However, the patterns observed in other regions did not appear to point towards the same trend. In the left precentral gyrus, the reversed patterns of interactions between frequency and length effects between the two groups suggest that Hebrew bilinguals were relying on phonological recoding strategies for real-word reading to a greater extent than the Spanish bilinguals within this region. At the same time, the lexicality effects seen in this region were stronger in the Hebrew bilinguals, particularly for short letter-strings relative to their Spanish counterparts, resulting in a null length effect for non-words. In contrast, the Spanish bilinguals showed no difference in lexicality effects between short and long letter-strings, and a significant effect of length for non-words. These patterns suggest that sub-articulatory processes for long non-words required more neural resources for the Spanish bilinguals relative to the Hebrew bilinguals, indicating that in the case of non-words, the Spanish bilinguals were relying on phonological processing strategies to a greater extent than the Hebrew bilinguals.

In the left inferior parietal lobule the pattern of frequency and lexicality effects for short letter-strings were almost identical between the two groups. For long letter-strings however, while the native Spanish speakers showed a marked increase in activation throughout all types of stimuli, in the native Hebrew speakers the observed increase was moderate, suggesting that in this group, phonological processing resources for long letter-strings may have been diverted elsewhere, perhaps to the postcentral gyrus, where activation for long letter-strings was strong and increased markedly as a function of frequency in both groups. In these regions therefore, there was also evidence for a grater reliance on phonological processing by Spanish bilinguals relative to Hebrew bilinguals.

The left inferior occipital gyrus was more strongly activated in each group's native language relative to ESL. Within this region, both groups showed a similar negative interaction between lexicality and length, suggesting that more processing resources were required for identifying short relative to long non-words. This pattern was similar in Hebrew, but reversed in Spanish, and indeed in English as a native language, indicating an effect of orthographic transparency on non-word processing. For real words however, while the Spanish bilinguals showed a positive frequency by length interaction, the Hebrew bilinguals showed no interaction between these effects, suggesting that the Spanish bilinguals were resorting to sequential orthographic assembly in ESL to a greater extent than the Hebrew bilinguals. Similarly, in the right middle occipital gyrus, both groups showed similar patterns of interactions, though Spanish bilinguals showed stronger length effects for real words relative to the Hebrew bilinguals, suggesting that in this region too, Spanish bilinguals were relying on sequential orthographic assembly to a greater extent than the Hebrew bilinguals. Interestingly, this region was more strongly activated in ESL relative to Hebrew, and specifically activated in ESL relative to Spanish, indicating that this region is sensitive to language dominance to a greater extent than to orthographic transparency.

Taken together, the observed pattern of activation in ESL differed from those seen in the native language, with respect to attentional and linguistic demands associated with reading in a less dominant language, and in terms of strategic demands associated with reliance upon lexical and sublexical processing, in keeping with the level of orthographic transparency of English, relative to the native languages. At the same time, the group differences observed in the patterns of frequency, length and lexicality effects within regions commonly activated in ESL were somewhat conflicting. While the patterns observed in the left precentral gyrus, left parietal cortex and bilateral occipital cortex were suggestive of a transfer of strategy from the native languages to reading in ESL, the observed patterns within the left inferior frontal gyrus, right middle temporal gyrus and right fusiform gyrus indicated that within these regions the adaptations employed by bilinguals for reading in their less dominant language were in keeping with the level of orthographic transparency of English, relative to the native languages, although there was also some evidence to suggest an exaggerated reliance on phonological recoding strategies by the Hebrew bilinguals, relative to their Spanish counterparts. Therefore specific patterns of regional activation related to reading in a second language may partly corroborate the proposed transfer of reading strategy from the native language (Muljani et al, 1998; Wang et al, 2003), although the patterns that ultimately emerged in the behavioural data[19] seem to point towards an efficient adaptation by the native Spanish bilinguals, and a somewhat less efficient adaptation by the native Hebrew bilinguals, whereby the availability of phonetic information in the form of written vowels in English, which does not exist in Hebrew, has led to an increased reliance on this information for the identification of words and non-words in ESL.

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[19] Recall that in Experiment 1, the relatively high proportion of word substitution errors made by Hebrew bilinguals in ESL hinted towards some transfer of the native strategy, which may be reflected by the activation patterns observed in the precentral gyrus, IPL and occipital cortex. This will be addressed in the discussion of Experiment 5

4.3 General discussion

The two fMRI experiments reported in this chapter aimed to visualise the neural correlates of reading in Spanish, English and Hebrew, assess the extent to which the graded levels of orthographic transparency of these three languages influenced the reading strategies employed by native readers, and examine the type of adaptation employed for reading in English as the midpoint of the orthographic transparency continuum, by bilinguals, native speakers of the two extremities of the continuum; Spanish and Hebrew, respectively.

Consistent with previous monolingual, bilingual and multilingual neuroimaging studies, reading in the three languages was associated with a largely shared network of widely distributed, predominantly left-lateralised cortical regions, also involved in spoken and heard language processing (Pugh et al, 1996; Fiez et al, 1999; Wydell et al, 2003; McDermott et al, 2003; Joubert et al, 2004; Klein et al, 1994; D'esposito & Alexander, 1995; Kim et al, 1997; Deahaene et al, 1997; Yetkin et al, 1996; Chee et al, 1999; Pu et al, 2001; Hernandez et al, 2000; Paulesu et a, 2000; Hernandez et al, 2001; Vingerhoets et al, 2003; Briellmann et al, 2004; Meschyan & Hernandez, 2005; Halsband, 2006). Concurrently, reading in each language was related to some preferential activation within regions associated with lexical / semantic and sublexical / phonological processing, respectively, in keeping with the graded levels of orthographic transparency of these languages. Moreover, in conjunction with the anatomical data, the observed effects of frequency length and lexicality within regions of interest support the behavioural naming patterns observed in Experiment 1, indicating that reading in the transparent Spanish entailed predominant (but not exclusive) reliance on phonological processing, reading in the opaque Hebrew entailed predominantly (but not exclusively) lexical / semantic processing while reading in English as a native language involved both types of strategy to a similar extent, thus corroborating previous findings demonstrating some distinct patterns of activation associated with reading in languages with varied orthographic characteristics (Paulesu et al 2000; Nakada et al, 2001; Tan et al, 2001; Liu & Perfetti, 2003; Valaki et al, 2003; Ding et al, 2003; Lee, et al, 2004; Meschyan & Hernandez, 2005; Siok et al, 2006; Simon et al, 2006), and the weak version of the Orthographic Depth Hypothesis (Katz & Frost, 1992).

As outlined in the introduction to this chapter, visualising the effects of frequency, length and lexicality within regions of interest was expected to shed light on some unresolved issues that emerged from the behavioural data in Experiment 1. One of these issues related to the unusually strong length effect observed in Hebrew high-frequency words, which decreased systematically as the frequency of items decreased, giving rise to the negative interaction between frequency and length and between length and lexicality. Results of Experiment 2 confirmed that this effect was of linguistic nature and was attributed to a strategic dilemma faced by readers of opaque orthographies, particularly in the presence of non-words, whereby upon initial exposure the cognitive system attempted a sequential assembly of written material, which was promptly aborted in favour of addressed lexical / semantic processing due to the inefficiency of sequential assembly in the absence of written vowels. Importantly, the results of Experiment 4, evidenced traces of this dilemma reflected by significant Hebrew word-length effects in the extrastriate occipito-temporal cortex, bilaterally, despite the blocked presentation of experimental stimuli and the isolation of non-words to the final two blocks, as well as the stringent subtraction approach and masking procedure, which yielded principally linguistic-related activation (confirmed by the absence of word-length effects in the occipital cortex in Spanish and English). This important finding therefore points towards the notion that the strategic dilemma in readers of an opaque orthography occurred even before exposure to non-words, thus corroborating previous behavioural data showing that the cognitive system's 'default' reading strategy regardless of orthographic transparency is assembled, rather than addressed phonology (i.e. Phonological Hypothesis; c.f. Frost, 1994; 1995).

Another issue which required clarification was related to reading in ESL. While both bilingual groups showed similar patterns of naming accuracy in their second language, the observed naming latency patterns were suggestive of an exaggerated reliance on phonological recoding by the Hebrew bilinguals relative to their Spanish counterparts. This was reflected as slower naming of long low-frequency words and non-words by Hebrew bilinguals relative to Spanish bilinguals.

The anatomical data reported in both fMRI experiments were in keeping with previous bilingual studies assessing the effects of language proficiency on patterns of neural activation, showing that reading in a second language entailed some overlapping but more extensive activation within left-lateralised regions, mostly those involved in sublexical / phonological processing, within medial frontal regions implicated in working memory and attentional processes (Perani et al, 1996; Dehaene et al, 1997; Kim et al, 1997; Hernandez et al, 2001; Wattendorf et al, 2001; Watenburger et al, 2003), as well as some distinct activation within frontal and temporal homologous language processing regions in the right hemisphere (Dehaene et al, 1997; Proverbio et al, 2002; Pillai et al, 2003). At the same time, the differences between the activation patterns seen in each native language and ESL were in line with studies suggesting that even in a second language, the level of orthographic transparency may affect the types of processing strategies and thus lead to some preferential activation within certain cortical regions (Nakada et al, 2001; Tan et al, 2001; Liu & Perfetti, 2003; Valaki et al, 2003; Ding et al, 2003; Lee, et al, 2004, Siok et al, 2006; Meschayn & Hernandez, 2005; Simon et al, 2006). Indeed, both bilingual groups showed marked overlap between regions commonly activated in ESL in both experiments, suggesting that each group had similarly adapted the reading strategies to their second language. Nevertheless, the observed patterns of frequency, length and lexicality effects in Experiment 4 suggested that some transfer of processing strategies employed preferentially in the native languages may have taken place, in keeping with findings of Muljani et al (1998) and Wang et al (2003) examining the differences in reading strategies employed for English by readers of Chinese and Indonesian or Korean, respectively. However, unlike in those studies, this transfer did not emerge clearly in the behavioural data of the present study. In fact, the present fMRI data provided some supporting evidence for the proposed exaggerated use of phonological processing by Hebrew bilinguals. This evidence emerged in Experiment 3 while bilinguals were reading low-frequency words in ESL, where the Spanish bilinguals showed activation only within the left inferior parietal lobule, whereas the Hebrew bilinguals showed overall more extensive activation, including left inferior parietal lobule as well as the posterior superior temporal gyrus and inferior frontal gyrus. In Experiment 4 this was most clearly seen by the anatomical pattern of activation within the inferior frontal cortex, where the Spanish bilinguals showed preferential activation within anterior portions, while the Hebrew bilinguals activated more posterior regions of the cortex.

A more detailed examination of this issue could be conducted in future studies, as suggested by Meschyan and Hernandez (2005). In their discussion, these authors proposed a future study comparing the processes involved in reading with Spanish-English bilinguals who were more proficient in their native language relative to English, as was done presently, as well as examining the alternative situation, whereby native English speakers with Spanish as their second language would show reversed patterns of activation relating to language proficiency but similar patterns related to orthographic transparency. In the present investigative framework comprising three languages, an efficient way to examine the influence of language proficiency, orthographic transparency and the proposed exaggerated reliance on phonological processing by Hebrew readers would be to test trilinguals. This was the aim of the final experiment of the present study, reported in the next chapter.

Chapter 5

Completing the Picture: Reading in Three languages; a Trilingual Comparison

5.1 Introduction

So far, the experiments reported in the present study have focussed on the reading strategies employed by bilinguals for reading in Spanish, Hebrew and English as a second language. The present findings have so far been largely consistent with previous bilingual studies, demonstrating that language proficiency and levels of orthographic transparency play important roles in the strategies employed by bilinguals for reading in their two languages (e.g. de Groot et al, 2002; Lemhöfer et al, 2008; Meschyan & Hernandez, 2005; Simon et al, 2006). Moreover, while the findings in Experiments 1, 3 and 4 showed that reading in each native language replicated and extended previous results supporting the currently accepted version of the Orthographic Depth Hypothesis (Katz & Frost, 1992), reading in ESL by native Spanish bilinguals and native Hebrew bilinguals gave rise to somewhat different patterns, which were not entirely in keeping with previous bilingual studies, suggesting that the predominant strategy used for reading in the native language may be transferred to the second language (e.g. Muljani et al, 1998; Wang et al, 2003).

Rather, while the native Spanish bilinguals showed an efficient adaptation to the less transparent English, the native Hebrew bilinguals appeared to show an exaggerated reliance on phonological assembly for reading in the relatively more transparent language. The possibility of a ‘compensatory mechanism’ was therefore put forward, whereby these participants, forced to use lexical knowledge to great extent in their native language, seized the presence of vowels as an opportunity to phonologically assemble words, at the expense of considerably delaying reaction time. As argued in Chapters 3 and 4, this notion is in line with previous findings of heavy reliance on phonological assembly in vowelised Hebrew (Frost, 1994, 1995).

Since bilingualism is the simplest form of multilingualism and a reliable methodological tool for comparison, it is not surprising that the majority of studies focussed on multiple language processing have relied on bilinguals as experimental participants. Within the current framework of investigation, whereby the comparative component is of three languages, conducting a trilingual study was deemed crucial in order to complete the picture.

Previous trilingual studies, aimed at extending current knowledge on bilingualism have relied on western European languages with common scripts and relatively similar levels of orthographic transparency (e.g. Lemhöfer et al, 2004, for German, Dutch, and English; Van Hell & Dijkstra, 2002; Vingerhoets et al, 2003, for Dutch, French and English; Wattendorf et al, 2001; 2003, for German, French and English). As outlined in Chapter 2, these have corroborated the view that multiple languages are subserved by common processing mechanisms, represented in largely overlapping neural substrates, with differences emerging as a result of language proficiency, whereby processing of less dominant languages requires additional cognitive demand, relative to the native language. To date, to my knowledge, no trilingual study has compared the strategies involved in reading alphabetic languages which can be viewed as extremities of the orthographic transparency continuum. Indeed, the only trilingual study to have included Hebrew (Abu-Rabia & Siegel, 2003), focussed on examining reading skills of native Arabic children, with Hebrew and English as additional languages.

The present experiment was aimed at extending the present findings by behaviourally examining the extent to which lexical / semantic and sub-lexical / phonological processing may be associated with reading in Spanish, English and Hebrew, in trilinguals.

5.2 Experiment 5:
Naming words and non-words in trilinguals

5.2.1 Introduction

Although trilingualism is a widely common phenomenon, the particular combination of languages presently investigated does not exist in any official form. The most likely place to find trilinguals of Spanish, English and Hebrew was therefore Israel; a country based on immigration, with Hebrew and Arabic as the official languages, English as the most widely used foreign language (Amara, 2006), and a myriad of cultural and national minority populations who have retained their native languages. Among these is Spanish (Hadas, 1992). In 2005 it was estimated that 20% of Israel’s population was Spanish-speaking (Ariza, 2005). The present experiment therefore consisted of two groups of trilingual participants, residing in Israel; native Spanish speakers and native Hebrew speakers.

The underlying premise of this trilingual comparison was examining the naming patterns in all three languages within the same set of participants, which would strengthen the notion of the use of a compensatory mechanism in native Hebrew readers, who provide a reliable 3-point comparison of the three languages. In addition, examining the reading patterns in Hebrew by native Spanish trilinguals would provide important insight on the strategies used to cope with the extremely opaque orthography of Hebrew as a non-native language compared to ESL, since relatively few studies have addressed this issue (e.g. Shimron & Sivan, 1994; Gollan, Forster & Frost, 1997; Abu-Rabia & Siegel, 2003; Benuck & Peverly, 2004).

To my knowledge, an experiment of this nature examining the differences in reading strategies between Hebrew, English and Spanish, or indeed between Hebrew and Spanish, has not been reported previously. It was therefore hoped that findings from the present experiment would fill this gap in the literature and complete the picture of reading in three languages of contrasting levels of orthographic transparency.

5.2.2 Method

5.2.2.1 Participants

Forty trilinguals[20] (23 female, 17 male), aged between 19 and 65 (mean age 39 years ±13; median=37) were recruited by word of mouth for participation in the

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[20] The original sample comprised 44 participants, 4 of which were eventually excluded from the analysis.

present experiment[21]. All had received between 12 and 26 years of formal education (mean 17 years ±3), and had no history of learning disability or reading impairment. Twenty participants (10 female, and 10 male) had been raised in a Spanish-speaking country (Chile, Argentina, Mexico, Peru and Uruguay) and had received Hebrew and English tuition since primary school. These participants had immigrated to Israel between the age of 10 and 18, and received subsequent formal education in Hebrew. Seven participants from this group had also lived in an English-speaking country for an average of 2.6 years (±1.5), and/or had attended an English-speaking school or university for an average of 1.6 years (±0.5). These are referred to henceforth as native Spanish trilinguals. The remaining 20 participants (13 female, 7 male) had been raised in Israel by Spanish-speaking immigrant parents who spoke Spanish at home, and/or had lived in a Spanish speaking country for a minimum of 1 year. Seventeen participants had also lived in an English-speaking country for an average of 3 years (±2), and/or had attended an English-speaking school or university for an average of 5 years (±3). Participants from this group are therefore referred to as native Hebrew trilinguals. Demographic details of trilingual participants are summarised in Table 5-1.

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[21] Note that the considerably large range of ages was due to the native Spanish participants being on average significantly older than native Hebrew participants, as can be seen in Table 5-1. To anticipate, the statistical analysis reported below accounted for the group age difference by including “age” as a covariate.

Table 5-1 *Trilingual participants' demographic details*

	Spanish Trilinguals (N=20)		Hebrew Trilinguals (N=20)	
	Range	Mean (SD)	Range	Mean (SD)
Age (years)	**19-65**	**48 (12)**	**19-57**	**31 (8)**
Formal education (years)				
Overall	12-26	18 (3)	12-23	17 (3)
Spanish	**2-21**	**13 (4.5)**	**1-8**	**3 (2)**
Hebrew	**1-13**	**5 (3.5)**	**8-18**	**12 (3)**
English	**0-3**	**0.5 (0.8)**	**0-12**	**3 (3)**
Age of acquisition (AoA, years)*				
Spanish	Native		0-31	8 (9.5)
Hebrew	0-33	11.5 (8.8)	Native	
English	**6-28**	**12.3 (5)**	**3-13**	**8.5 (2.6)**
Length of residence (LoR, years)				
Spanish-speaking country	**7-33**	**21 (7)**	**0-14**	**5 (4)**
Israel (Hebrew-speaking)	3-40	24 (10)	13-47	23 (9)
English-speaking country	0-5	0.6 (1)	0-8	1.5 (2)
Language exposure (hours per week)				
Spanish	1-60	18 (17.6)	1-60	10.6 (17.5)
Hebrew	50-70	68 (5)	10-90	63 (26)
English	**1-70**	**18.7 (16.5)**	**3-70**	**36.5 (27)**

Figures in bold indicate a statistically significant difference between the two trilingual groups, as revealed by a one-way ANOVA:
Age; $F_{(1,39)}$=26.99, p<0.001
Formal education in Spanish; $F_{(1,39)}$=84.36, p<0.001
Formal education in Hebrew; $F_{(1,39)}$=44.87, p<0.001
Formal education in English; $F_{(1,39)}$=12.33, p<0.001
AoA English; $F_{(1,39)}$=8.59, p<0.006
LoR Spanish; $F_{(1,39)}$=72.81, p<0.001
Hours of exposure to English $F_{(1,39)}$=6.24, p<0.02
** Note that for participants who considered themselves as native speakers of the group's less dominant language, AoA was annotated as 0.*

5.2.2.2 Experimental procedure

Inclusion criteria, stimuli and apparatus used in the trilingual experiment were as described in Chapter 3. Experimental procedure was identical to that used Experiment 1, with the exception of the number of language blocks comprising each test. In the present experiment both trilingual groups were presented with the 3 language blocks, in a counterbalanced order.

5.2.3 Results

5.2.3.1 Naming Latency

Naming latencies for correct responses were averaged across participants for each language and each condition. Within each participant, response latencies in each condition falling outside the range of 2.5 standard deviations from the respective mean were discarded, and the mean was recalculated. Outliers accounted for less than 2% of all trials. Other discarded trials were those where the voice-key had been triggered by environmental noise or where participant response was not recorded due to voice-key insensitivity. These trials accounted for less than 4% of all trials. Table 5-2 shows the mean latencies of correct responses, for each experimental condition, obtained by the two trilingual groups in the three languages.

Regression analysis revealed no effect of gender or level of formal education on overall naming latency (please see Appendix 9). The statistical significance of naming latency patterns in the three languages across the two trilingual groups was therefore assessed using repeated-measures analysis of variance (ANOVA) across subjects (F1) and across items (F2). However, as seen in Table 5-1, the Spanish trilinguals were significantly older than the Hebrew trilinguals, and regression analysis revealed a significant effect of age on naming latency in Hebrew and English. Consequently, the naming patterns in Hebrew and English were re-analysed using repeated measures analysis of co-variance (ANCOVA) with age as a covariate, across subjects only. Table 5-3 shows the adjusted mean response latencies for Hebrew and English. The effects of word-frequency, string-length and lexicality on naming latency are summarised in Table 5-4, and adjusted effects in Table 5-5.

As seen in Table 5-3, each trilingual group exhibited overall faster naming in the respective native language, i.e. native Spanish speakers were overall faster in Spanish naming relative to the native Hebrew speakers, who in turn were overall faster in Hebrew naming relative to the native Spanish speakers. In addition, English naming was slightly faster by participants from the native Hebrew group relative to the native Spanish speakers. Both trilingual groups, however, showed a similar naming pattern in all languages, whereby high-frequency words were named faster than low-frequency words, short words were named faster than long words, and real words were named faster than non-words. Below is a detailed description of the between-group comparison of naming performance in each language.

Table 5-2 *Mean naming latency in milliseconds (ms), achieved by each trilingual group in each language (figures in brackets represent standard deviations from the mean)*

	Spanish Trilinguals			Hebrew Trilinguals		
	Spanish	Hebrew	English	Spanish	Hebrew	English
High-frequency short words	787 (114)	914 (163)	823 (159)	800 (93)	711 (88)	733 (82)
High-frequency long words	810 (128)	1073 (207)	843 (125)	899 (123)	801 (89)	785 (105)
Low-frequency short words	836 (146)	1072 (234)	903 (180)	876 (136)	780 (103)	793 (118)
Low-frequency long words	909 (144)	1247 (288)	981 (213)	1088 (187)	861 (130)	870 (167)
Overall word naming latency	835 (127)	1077 (216)	888 (162)	916 (126)	788 (96)	795 (113)
Short non-words	940 (168)	1465 (375)	1012 (332)	980 (168)	1063 (327)	842 (149)
Long non-words	1058 (231)	1583 (375)	1095 (325)	1145 (215)	1083 (286)	977 (213)
Overall non-word naming latency	999 (193)	1524 (380)	1054 (325)	1062 (186)	1073 (301)	910 (178)

Table 5-3 *Age-adjusted means of naming latency in Hebrew and English (values for Spanish are as above) in milliseconds (ms; figures in brackets represent standard deviation for Spanish and standard errors for Hebrew and English)*

	Spanish Trilinguals			Hebrew Trilinguals		
	Spanish	Hebrew	English	Spanish	Hebrew	English
High-frequency short words	787 (114)	894 (34)	805 (33)	800 (93)	732 (34)	751 (33)
High-frequency long words	810 (128)	1043 (41)	821 (30)	899 (123)	831 (41)	806 (30)
Low-frequency short words	836 (146)	1048 (47)	874 (39)	876 (136)	804 (47)	823 (39)
Low-frequency long words	909 (144)	1214 (58)	931 (48)	1088 (187)	894 (58)	921 (48)
Overall word naming latency	835 (127)	1050 (43)	858 (36)	916 (126)	815 (43)	825 (36)
Short non-words	940 (168)	1392 (93)	975 (67)	980 (168)	1135 (93)	880 (67)
Long non-words	1058 (231)	1499 (84)	1044 (71)	1145 (215)	1167 (83)	1029 (71)
Overall non-word naming latency	999 (193)	1446 (87)	1009 (68)	1062 (186)	1151 (87)	954 (68)

***Table 5-4** Effects of word-frequency, string-length and lexicality on naming latency in the two trilingual groups (ms and % effect)*

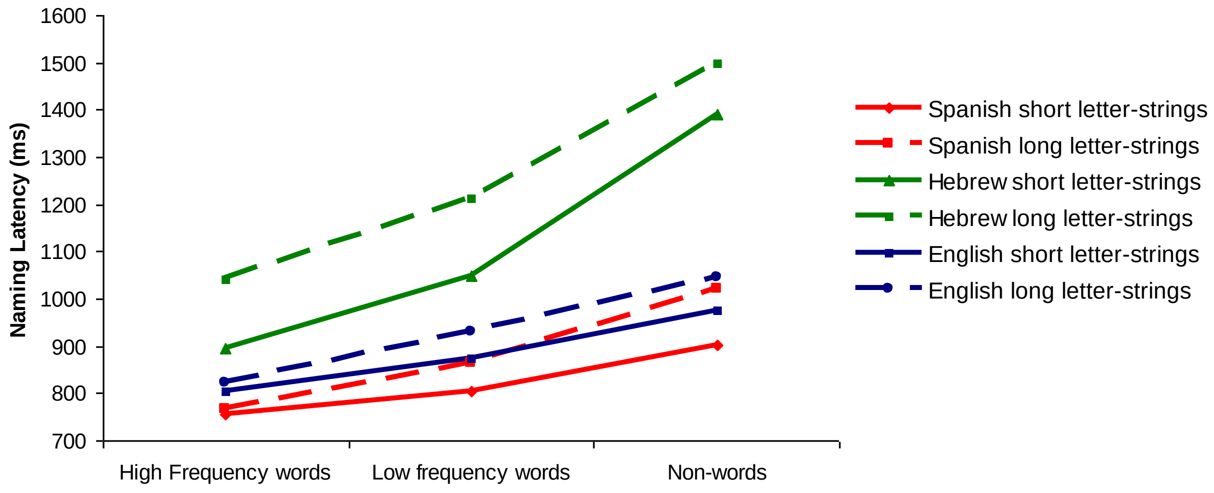
		Spanish Trilinguals						Hebrew Trilinguals					
		Spanish		Hebrew		English		Spanish		Hebrew		English	
		ms	%	ms	%	ms	%	ms	%	ms	%	ms	%
Frequency effects (low – high)	Short words	48	5	157	14	80	8	75	8	69	7	60	7
	Long words	98	10.5	174	13	138	13	188	16	59	6	84	9
	Overall	73	8	165	13	109	11	132	13	64	6.5	72	8
Length effects (long – short)	High-frequency words	23	2	159	14	19	2.5	98	11	90	11	52	6
	Low-frequency words	73	8	175	13.5	78	7	212	19	80	8.7	76	8
	Overall words	48	5	167	14	48	5	155	15	85	10	64	7
	Non-words	118	10	118	8	82	7.5	164	14	20	2	135	13
Lexicality effects (nw – words)	Short letter-strings	128	13	471	30	149	12	141	14	317	26	78	8.5
	Long letter-strings	198	18	422	25	183	14	150	12	251	20	149	13
	Overall	163	16	447	27.5	166	13	146	13	284	23	114	11.5

***Table 5-5** Age-adjusted effects of word-frequency, string-length and lexicality on naming latency in Hebrew and English (ms and % effect)*

(Values in Spanish are as above)

		Spanish Trilinguals						Hebrew Trilinguals					
		Spanish		Hebrew		English		Spanish		Hebrew		English	
		ms	%	ms	%	ms	%	ms	%	ms	%	ms	%
Frequency effects (low – high)	Short words	48	5	154	15	69	8	75	8	72	9	72	9
	Long words	98	10.5	171	14	110	12	188	16	63	7	115	12
	Overall	73	8	162	14	89	10	132	13	67	8	93	11
Length effects (long – short)	High-frequency words	23	2	149	14	16	2	98	11	99	12	55	7
	Low-frequency words	73	8	166	14	57	6	212	19	90	10	98	11
	Overall words	48	5	157	14	36	4	155	15	94	11	76	9
	Non-words	118	10	107	7	69	7	164	14	32	3	149	14
Lexicality effects (nw – words)	Short letter-strings	128	13	421	30	135	14	141	14	367	32	93	10
	Long letter-strings	198	18	370	25	168	16	150	12	304	26	165	16
	Overall	163	16	396	27.5	152	15	146	13	336	29	129	13.5

a. Spanish trilinguals



b. Hebrew trilinguals

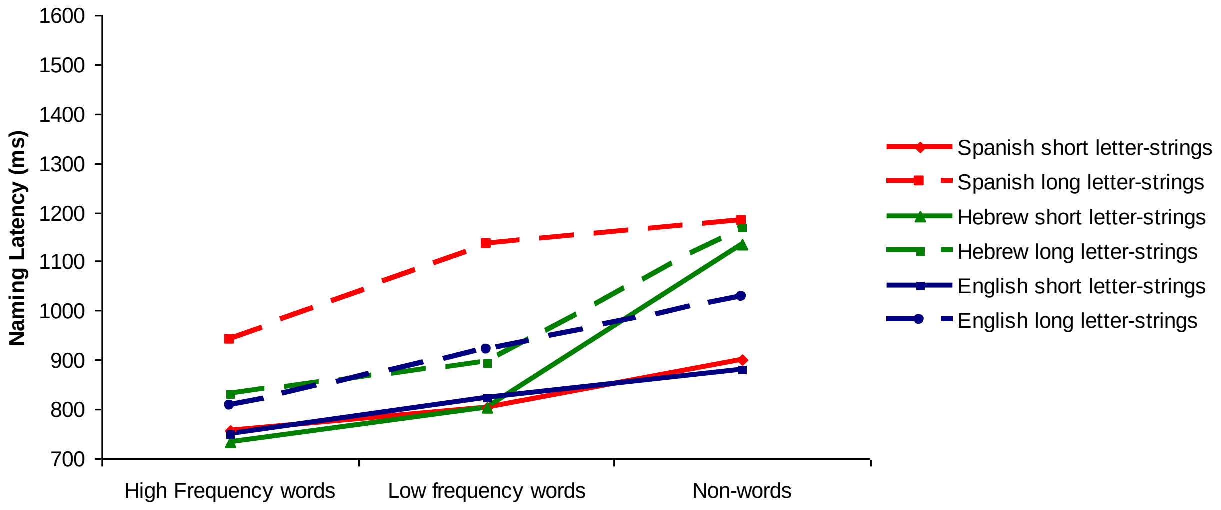


Figure 5-1 *Naming latency in Spanish (standard means), English and Hebrew (age-adjusted means) by: a. Native Spanish trilinguals; b. Native Hebrew trilinguals*
For clarity, error bars are not included in the figure, but can be viewed in Table 5-3

5.2.3.1.1 Naming in Spanish

As shown in Figure 5-1a, the Spanish trilinguals exhibited a naming pattern in their native language, which was identical to that observed for the native Spanish bilinguals in Experiment 1, i.e. an increase in response latencies between high-frequency words (798 ms), low-frequency words (872 ms) and non-words (999 ms), a systematic increase in frequency effect as a function of length (5% increase for short words and 11% increase for long words) and a systematic increase in length effect as a function of lexicality (5% increase for words and 10% increase for non-words). The Hebrew trilinguals (Fig. 5-1b) exhibited slower naming and stronger effects of frequency and length in Spanish (shown in Table 5-5) and a similar pattern to their native Spanish counterparts for real words, with an average RT of 849 ms for high-frequency words and 982 ms for low-frequency words, and an 8% increase in frequency effect for short words and 16% increase for long words. However, the proportional difference in reaction time between long words and long non-words (12%) was smaller than the difference between short words and short non-words (14%) in this group[22]. In keeping with these observations, the 3X2 ANOVA revealed significant main effects of frequency: $F1_{(2,76)} = 131.19$, $p < 0.0001$; $F2_{(1,56)} = 100.81$, $p<0.0001$ and length: $F1_{(1,38)} = 117.75$, $p<0.0001$; $F2_{(1,28)} = 120.02$, $p<0.0001$. The main effect of group was significant in the item analysis, $F2_{(1,28)} = 53.82$, $p<0.0001$, but not in the subject analysis ($F1_{(1,38)} = 2.62$, $p=0.11$). A close examination of the data revealed that this discrepancy between

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[22] A subjective review conducted at the end of the experimental session revealed that some low-frequency words were novel for Hebrew trilinguals e.g. *fosa, puya, zuro, boñiga, marjal, pábulo and rebujo*. Therefore the weaker length effect for non-words relative to low-frequency words was attributed to inferior Spanish proficiency by this group of trilinguals, which resulted in slower naming of long low-frequency words.

the subject and item analyses stemmed from the fact that on average, 43 out of 45 long items and 35 out of 45 short items were named faster by the native Spanish speakers, although not all participants from this group produced faster naming latencies than all native Hebrew participants, on all conditions. In fact, as seen in Figure 5-1, on average, participants from both groups exhibited similar naming latencies for short letter-strings in Spanish, with large group differences observed for long letter-strings. Pairwise comparisons with Bonferroni correction revealed that Hebrew trilinguals were significantly slower than Spanish trilinguals while naming high-frequency long words: 89 ms difference, $p<0.03$, and low-frequency long words: 179 ms difference, $p<0.002$. Concordantly, Hebrew trilinguals exhibited a significantly stronger effect of frequency for long words: 6% difference, $p<0.02$, as well as significantly stronger length effects for high-frequency words: 8% difference, $p<0.001$, and low-frequency words: 11% difference, $p<0.001$. The interaction between group and length was thus significant, $F1_{(1,38)} = 16.78$, $p<0.0001$; $F2_{(1,28)}= 16.94$, $p<0.001$, while the interaction between group and frequency was not ($F1_{(2,76)} =2.95$,$p=0.77$; $F2_{(2,56)}= 1.96$, $p=0.17$), since the native Spanish speakers showed only marginally weaker effects of frequency relative to the Hebrew speakers (Table 5-5).

Importantly, the significant frequency by length interaction: $F1_{(2,76)} =16.74$, $p<0.0001$; $F2_{(2,56)}=4.82$, $p<0.01$ indicates that the length effect was strongly modulated by frequency in Spanish. As seen in Figure 5-1, in the native Spanish group length effect systematically increased between high-frequency words (2%) low-frequency words (8%) and non-words (10%), as was also observed in

Experiment 1. In the native Hebrew group this increase was seen for real words, with a considerable increase of length effect between high-frequency (11%) and low-frequency words (15%). In keeping with these observations, the 3-way interaction (frequency x length x group) was not significant ($F1_{(2,76)} = 4.29$, $p=0.25$; $F2_{(2,56)}=1.12$, $p=0.33$), suggesting that the modulation of frequency effects by word-length was similar in both groups.

The 2X2 ANOVA for lexicality effects produced similar effects to the 3x2 comparison of frequency and length effects, whereby main effects of lexicality and length were strongly significant: $F1_{(1,38)} = 147.53$, $p<0.0001$; $F2_{(1,28)}=119.4$, $p<0.0001$, and $F1_{(1,38)} = 104.95$, $p<0.0001$; $F2_{(1,28)}=126.11$, $p<0.0001$, respectively, and main effect of group was significant across items, $F2_{(1,28)}=37.79$, $p<0.0001$, but not across subjects ($F1_{(1,38)} = 2.11$, $p=0.15$). The interaction between lexicality and group was not significant ($F1_{(1,38)} = 0.46$, $p=0.5$; $F2_{(1,28)}=0.37$, $p=0.55$), indicating that the magnitude of lexicality effects in Spanish was similar between the two groups, although the interaction between group and length was strong: $F1_{(1,38)} = 10.43$, $p<0.003$; $F2_{(1,28)}=12.48$, $p<0.001$, since native Hebrew speakers showed stronger length effects than their native Spanish counterparts. The lexicality by length interaction was significant in the subject analysis: $F1_{(1,38)} = 5.80$, $p<0.02$, but not significant in the item analysis ($F2_{(1,28)}= 2.09$, $p=0.16$), suggesting that lexicality modulated length effects in Spanish, though as shown in Table 5-5, this was seen only in the native Spanish group, who showed a 5% increase in lexicality effect between short and long letter-strings, while the native Hebrew group showed a 2% decrease, since length effect for non-words in this group

(14%) was weaker than for low-frequency words (19%). The pairwise comparison revealed that the magnitude of lexicality effect was significantly stronger in the native Spanish speakers for long letter-strings: 6% difference, $p<0.02$, though the overall lexicality effect was not significantly different between the two groups (3% difference, $p=0.14$), and therefore the 3-way interaction (lexicality x length x group) was not significant in either subject or item analysis ($F1_{(1,38)}=3.45$, $p=0.07$; $F2_{(1,28)}= 1.04$, $p=0.32$).

5.2.3.1.2 Naming in Hebrew

As shown in Figure 5-1b, Hebrew trilinguals showed naming patterns in their native language which were identical to those observed in Experiment 1, whereby a strong length effect was seen for high-frequency words (12%), which systematically *diminished* as frequency decreased (10% for low-frequency words and 3% for non-words), and a considerable lexicality effect, which was stronger for *short* (32%) relative to long letter-strings (26%). As shown in Table 5-3, the Spanish trilinguals showed significantly slower naming latencies relative to Hebrew trilinguals in all 6 conditions: p values ≤ 0.001, as well as stronger effects, with significant differences observed for the magnitude of frequency effect for short: 5% difference, $p<0.006$, and long words: 7% difference, $p<0.02$, as well as length effect for low-frequency words: 5% difference, $p<0.04$. The naming patterns, however, were similar to those observed for the Hebrew trilinguals, with a strong length effect for high (14%) as well as low-frequency words (14%), and a considerably weaker effect for non-words (7%). In addition, stronger lexicality effect was observed for short (30%) relative to long letter-strings (25%).

Correlation analysis between participants' demographic data and naming latency revealed significant relationship between formal education in Hebrew and overall naming latency in the native Spanish trilinguals: $r=0.5$, $p<0.04$, indicating that those participants who had spent more time receiving formal education in Hebrew tended to show overall faster naming in this language. In addition, significant relationships were found between formal education and naming latency of short high-frequency words: $r=0.48$, $p<0.03$, short low-frequency words: $r=0.47$, $p<0.04$, and particularly long low-frequency words: $r=0.51$, $p<0.02$.

The 3X2 ANCOVA, therefore revealed a main effect of frequency: $F_{(2,74)}=97.45$, $p<0.001$, a main effect of length: $F_{(1,37)}=113.88$, $p<0.001$, and a main effect of group: $F_{(1,37)}=26.86$, $p<0.001$. Since age was treated as a covariate in this analysis, the main effect of age was not significant ($F_{(1,37)}=2.50$, $p=0.12$), and neither were any interactions with age (all F values < 2.53, all p values > 0.23). The interactions between group and frequency, and between group and length were significant: $F_{(2,74)}=5.80$, $p<0.005$, and $F_{(1,37)}=18.83$, $p<0.001$, respectively, since native Hebrew speakers exhibited overall weaker effects of frequency and length in their native language, relative to the native Spanish speakers (Table 5-5)

The interaction between frequency and length was significant in Hebrew: $F_{(2,74)}=4.43$, $p<0.02$, indicating that frequency effects were modulated by word length, though as can be seen in Figure 5-1a and b, the direction of the interaction was in the opposite direction to that seen in Spanish. The native Hebrew speakers showed a 2% *decrease* in length effect between high (12% length effect) and low-frequency words (10% length effect) and an 8% decrease in length effect between words (11% length effect) and non-words (3% length effect). The native Spanish speakers showed a somewhat different trend, with 0% difference observed in the magnitude of length effect between high- and low frequency words[23] but a 7% *decrease* in length effect between words and non-words. The 3-way interaction (frequency x length x group) was therefore not significant ($F_{(2,74)}=0.27$, $p=0.76$).

The 2X2 ANCOVA for lexicality effects revealed a main effect of lexicality: $F_{(1,37)}=99.58$, $p<0.001$, a main effect of length: $F_{(1,37)}==66.47$, $p<0.001$, and a main effect of group: $F_{(1,37)}=24.32$, $p<0.001$. As in the 3X2 ANCOVA, the main effect of age was not significant ($F_{(1,37)}=2.77$, $p=0.10$) and neither were any interactions with age (F values < 2.78, p values > 0.11). Significant interactions were found between lexicality and group: $F_{(1,37)}=4.93$, $p<0.03$, and between length and group: $F_{(1,37)}=14.08$, $p<0.001$, since the Spanish trilinguals showed larger differences in RT between short and long words and non-words, relative to native Hebrew speakers. Importantly, the interaction between lexicality and length: $F_{(1,37)}=6.29$, $p<0.02$ indicates a modulation of length effects by lexicality, though as described above, this interaction was in the opposite direction to that seen in Spanish, i.e. the difference in naming latency between short words and non-words was *larger* than the difference between long words and non-words. This was the case in both groups, thus resulting in a non-significant 3-way interaction ($F_{(1,37)}=0.13$, $p=0.72$). It

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[23] A subjective review conducted at the end of the experimental session revealed that some low-frequency words were novel for most Spanish trilinguals e.g. *עלם, טוזיג, עששית, נסיוב*. Therefore the 0% difference in length effect between high and low-frequency words was attributed to inferior Hebrew proficiency in this group of trilinguals, which resulted in slower naming of long low-frequency words, as was seen in Spanish naming by Hebrew trilinguals.

is important to note that the ANOVA for these data produced identical main effects and interactions to those reported above.

5.2.3.1.3 Naming in English

As shown in Figure 5-1b, the English naming patterns seen by the native Hebrew trilinguals are reminiscent of those seen by the native Hebrew bilinguals in Experiment 1, whereas the patterns seen by the native Spanish trilinguals (Fig. 5-1a) resemble those seen in Spanish in both Experiment 1 and the present experiment. Specifically, these participants showed very little difference in naming latency between short and long high-frequency words (2% length effect for high-frequency words), and a systematic increase in this difference as frequency decreased (6% for low-frequency words and 7% for non-words). While the trend was similar for the Hebrew trilinguals, the differences between short and long letter-strings were larger (7% for high-frequency words, 11% for low frequency words and 14% for non-words).

As can be seen in Table 5-3, Hebrew trilinguals were overall faster than Spanish trilinguals in English, particularly while naming short words and non-words. Pairwise comparisons therefore revealed significant group differences for high-frequency short words: 90 ms difference, $p<0.03$, low-frequency short words: 110 ms difference, $p<0.03$, and short non-words: 170 ms difference, $p<0.04$.

Correlation analysis between participants' demographic data and naming latency in English revealed a significant relationship between formal education in English and naming latency for English short low-frequency words in the native Hebrew trilinguals: $r=0.46$, $p<0.04$.

The 3x2 ANCOVA revealed main effects of frequency: $F_{(2,74)}=42.19$, $p<0.001$ and length: $F_{(1,37)}=76.85$, $p<0.001$. The main effect of group approached significance ($F_{(1,37)}=3.93$, $p=0.06$) in this analysis, though when age was not treated as a covariate the main effect of group was significant in the item analysis, $F2_{(1,28)}= 84.4$, $p<0.0001$, since all 90 English items were named faster by the native Hebrew speakers, relative to the native Spanish speakers. However, the interaction between frequency and group and between length and group were not significant in the ANCOVA ($F_{(2,74)}=1.51$, $p=0.23$ and $F_{(1,37)}=2.70$, $p=0.12$, respectively) nor in the AVOVA ($F1_{(1,38)} = 2.93$, $p=0.06$; $F2_{(2,56)}= 2.93$, $p=0.06$, $F1_{(1,38)} =2.55$, $p=0.12$; $F2_{(1,28)}= 1.54$, $p=0.23$, respectively) indicating that despite the overall faster naming by Hebrew trilinguals, naming patterns in English were similar between the two groups. Similarly, the main effect of age, and the interactions between age and other factors were not significant (F values < 3.20, p values > 0.08). As in Spanish and Hebrew, a significant interaction was revealed between frequency and length: $F_{(2,74)}=10.44$, $p<0.001$, and as can be seen in Figure 5-3, this interaction was similar to that seen for Spanish, and in the opposite direction of that seen in Hebrew, i.e. the effect of frequency was modulated by word-length such that the effect increased as frequency decreased. Since this modulation was similar for both trilingual groups, the 3-way interaction (frequency x length x group) was not significant ($F_{(2,74)}=1.45$, $p=0.24$).

The 2x2 ANCOVA for lexicality and length effects revealed main effects of lexicality: $F_{(1,37)}=77.69$, $p<0.001$, and length: $F_{(1,37)}=37.65$, $p<0.001$ since both trilingual groups exhibited faster naming for words, relative to non-words, and for short, relative to long letter-strings. As in the analysis of frequency and length effects, the main effect of group approached significance ($F_{(1,37)}=3.67$, $p=0.06$) in the ANCOVA, and was significant in the item analysis of the AVOVA: $F2_{(1,28)}=66.81$, $p<0.0001$. Similarly, the main effect of age and all interactions with this factor were not significant (F values < 2.69, p values > 0.11). In addition, there were no interactions between group and lexicality ($F_{(1,37)}=3.27$, $p=0.08$) or between group and length ($F_{(1,37)}=1.29$, $p=0.26$). The lexicality by length interaction was significant: $F_{(1,37)}=12.03$, $p<0.001$, indicating that length effect was modulated by lexicality in English, similar to Spanish. As shown in Table 5-5, this modulation was stronger for the native Hebrew speakers, who showed a 5% increase in lexicality effect between short and long letter-strings, relative to only 2% increase seen in native Spanish speakers, although the 3-way interaction was not significant ($F_{(1,37)}=1.51$, $p=0.23$).

5.2.3.1.4 Post-hoc assessment of between-language effects

As shown in Table 5-5, the native Spanish trilinguals exhibited weaker effects of frequency for short and long words, as well as length effects for high-frequency words in their native language relative to Hebrew and English, while length effects for low-frequency words were weaker in English, but stronger in Hebrew, and for non-words length effect was strongest in Spanish. Similarly, while lexicality effects for short letter-strings were weaker in Spanish than in the other two languages, for long letter-strings weaker effects were found in English. Importantly, lexicality effects were consistently and considerably stronger in Hebrew than in the other two languages. Pairwise comparisons with Bonferroni correction revealed significant differences between Spanish and Hebrew, and between English and Hebrew, but no significant differences were found between Spanish and English in this group. Specifically, the frequency effect for short words was significantly stronger in Hebrew than Spanish and English: $p<0.001$, and $p<0.04$, respectively. Similarly, length effect for high-frequency words was significantly stronger in Hebrew than Spanish and English: p values <0.001, though for low-frequency words the length effect was moderately stronger in Hebrew than in Spanish ($p=0.06$), but significantly stronger in *English* than in Hebrew: $p<0.03$, due to the inverse interaction between frequency and length in Hebrew. Lexicality effects for short letter-strings were markedly stronger in Hebrew than in Spanish and English: p values <0.001, while for long letter-strings the differences were somewhat smaller due to the inverse interaction between length and lexicality in this language, though still significant: $p<0.04$ for Spanish, and $p<0.001$ for English.

For the native Hebrew speakers, frequency effects for short words were almost identical in the three languages. As illustrated in Figure 5-1b, naming latencies for short high and low-frequency words were remarkably similar in the three languages, with differences emerging for long words, as well as short and long non-words. Frequency effects for long words were therefore weaker in the native language relative to Spanish and English. In contrast, length effects for high-frequency words were stronger in the native language relative to the other two languages, whereas for low-frequency words and non-words length effects were weaker in Hebrew. Importantly, as in the native Spanish trilinguals, lexicality effects in Hebrew were consistently and considerably stronger than in Spanish and English. The statistical analysis revealed that frequency effects for long words were significantly stronger in Spanish than Hebrew: $p<0.001$ and English: $p<0.001$, though the stronger effect in English relative to Hebrew did not reach statistical significance ($p=0.82$). In contrast, the length effect for high frequency words was significantly stronger in Hebrew than in English: $p<0.007$, as well as significantly stronger in Spanish than in English: $p<0.02$. The length effects for low-frequency words were significantly stronger in Spanish than both Hebrew and English: p values <0.001. Since length effect for non-words was practically absent in Hebrew, these effects in the other languages were significantly stronger: p values <0.001. Lexicality effects were significantly stronger in Hebrew than in English and Spanish for short letter-strings: p values <0.001, whereas for long letter-strings the difference between Spanish and Hebrew was significant: $p<0.03$, while the difference between English and Hebrew was not ($p=0.14$).

5.2.3.2 Naming accuracy

The number of errors made in each condition of each language are summarised in Table 5-6 and illustrated in Figure 5-4. Table 5-7 shows the values for the statistical analysis of effects of frequency, length and lexicality on naming accuracy. The types of errors made in each language are presented in Table 5-8 and can be visualised in Figure 5-5.

Table 5-6 *Incorrect responses [mean (SD)] made by each trilingual group in each language*

	Spanish Trilinguals			Hebrew Trilinguals		
	Spanish	Hebrew	English	Spanish	Hebrew	English
Overall naming errors	3.15 (3.2)	6.6 (3.8)	6.1 (3.1)	9.7 (4.5)	1.3 (1.4)	5.0 (2.9)
High-frequency short words	0.05 (0.2)	0.2 (0.4)	0.05 (0.2)	0.25 (0.6)	0	0.05 (0.2)
High-frequency long words	0.05 (0.2)	0.15 (0.4)	0.2 (0.5)	0.2 (0.4)	0	0.2 (0.4)
Low-frequency short words	0.45 (0.6)	1.7 (1.5)	1.2 (1.4)	0.95 (0.9)	0.4 (0.7)	0.3 (0.5)
Low-frequency long words	0.3 (0.7)	2.9 (1.9)	3.25 (0.8)	2.8 (1.6)	0.6 (0.9)	3.0 (1.3)
Short non-words	0.65 (0.9)	0.7 (0.7)	0.9 (0.9)	2.05 (1.8)	0.1 (0.3)	0.65 (0.9)
Long non-words	1.65 (1.8)	0.95 (0.9)	0.55 (0.7)	3.45 (1.5)	0.2 (0.4)	0.8 (1.2)

As seen in Table 5-6, similar to the naming latency data, each trilingual group exhibited the highest level of accuracy in the respective native language. The native Spanish speakers named 96.5% of Spanish words and non-words correctly, relative to only 92.6% and 93.2% in Hebrew and English, respectively. Within-group comparison (related samples Wilcoxon Signed Ranks test) revealed that the mean number of incorrect responses in Spanish was significantly lower than that of Hebrew and English in this group: $z=-2.81$, $p<0.005$ and $z=-2.68$, $p<0.007$, respectively, while the latter two did not differ ($z=-0.48$ $p=0.63$). Similarly, the native Hebrew speakers named 98.5% of Hebrew words and non-words correctly, relative to only 89.2% in Spanish and 94.4% in English. The statistical analysis for this group revealed that the differences between all three languages were significant; i.e. native Hebrew speakers made significantly more errors in Spanish than in Hebrew: $z=-3.92$, $p<0.0001$, significantly more errors in English than in Hebrew: $z=-3.63$, $p<0.0001$, as well as significantly more errors in Spanish than in English: $z=-3.31$, $p<0.001$. Between-group comparison (independent samples Wilcoxon Signed Ranks test) revealed that the mean number of errors in Spanish was significantly lower for the native Spanish speakers relative to the native Hebrew speakers: $W=258.5$, $z=-4.14$, $p<0.0001$, who in turn, exhibited a significantly lower mean number of errors in Hebrew: W=243, z=-4.56, p<0.0001. The error rate seen in English, although lower for the native Hebrew speakers than for native Spanish speakers, was not significantly different between the two groups (W=369.5 z=-1.12 p=0.28).

Correlation analyses showed that for native Spanish speakers, overall accuracy in Hebrew was related to the proportional length of residence in Israel: r=0.51, p<0.02, the number of years of formal education received in Hebrew: r=0.53, p<0.02, and age of acquisition of Hebrew: r=-0.54, p<0.01. Therefore, those participants who had been exposed to Hebrew for a longer period of time tended to make fewer errors than those who had had less exposure. No significant relationships were found between demographic factors and naming accuracy in English or Spanish in this group.

For native Hebrew speakers, overall accuracy in Spanish was related to the proportional length of residence in a Spanish speaking country: r=0.51, p<0.02. In addition, for this group, overall English accuracy correlated with the proportional length of residence in an English speaking country: r=0.44, p<0.05, and the number of years of formal education received in English: r=0.52, p<0.02. No significant relationships were found between demographic factors and naming accuracy in Hebrew for this group.

5.2.3.2.1 Effects of word-frequency, string-length and lexicality on naming accuracy

Table 5-7 *Statistical values for effects of word-frequency, length and lexicality on naming accuracy – within-group comparison – related samples Wilcoxon signed ranks test*

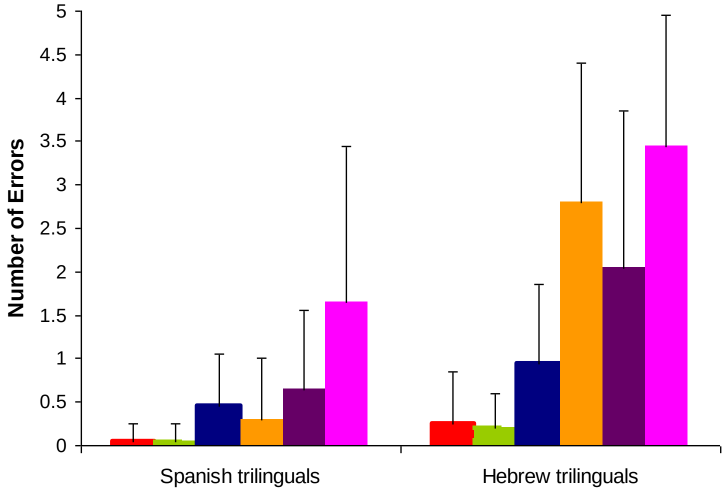
	Spanish Trilinguals			Hebrew Trilinguals		
	Spanish	Hebrew	English	Spanish	Hebrew	English
Frequency effect on naming accuracy of short words	**z=-2.53 p<0.01**	**Z=-3.2 p<0.001**	**z=-3.15 p<0.002**	**z=-2.70 p<0.007**	**z=-2.27 p<0.02**	z=-1.89 p=0.06
Frequency effect on naming accuracy of long words	z=-1.89 p=0.06	**Z=-3.55 p<0.0001**	**z=-3.97 p<0.0001**	**z=-3.75 p<0.0001**	**z=-2.59 p<0.01**	**z=-3.86 p<0.0001**
Length effect on naming accuracy of high-freq words	-	Z=-0.58 p=0.56	z=-1.73 p=0.08	z=-0.38 p=0.71	-	z=-1.73 p=0.08
Length effect on naming accuracy of low-freq words	z=-0.92 p=0.36	**Z=-3.4 p<0.001**	**z=-3.65 p<0.0001**	**z=-3.55 p<0.0001**	z=-0.95 p=0.34	**z=-3.68 p<0.0001**
Length effect on naming accuracy of non-words	**z=-2.59 p<0.01**	Z=-1.17 p=0.24	z=-0.72 p=0.47	**z=-2.27 p<0.02**	z=-0.82 p=0.41	Z=-0.5 p=0.62
Lexicality effect on naming accuracy of short letter-strings	z=-0.50 p=0.61	**z=2.64 p<0.008**	z=1.44 p=0.15	**z=-2.17 p<0.03**	z=1.61 p=0.11	z=1.51 p=0.13
Lexicality effect on naming accuracy of long letter-strings	**z=-2.89 p<0.004**	**z=3.19 p<0.001**	**z=3.96 p<0.001**	z=-0.82 p=0.42	**z=1.93 p<0.05**	**z=3.64 p<0.001**

Figures in bold highlight statistical significance

As shown in Table 5-7, since both trilingual groups tended to make more errors when naming low-frequency words relative to high-frequency words in all three languages, all within-group comparisons revealed significant or nearly significant frequency effects on accuracy. In contrast, string-length did not significantly affect word naming accuracy in each group's respective native language. However, in the less dominant languages participants tended to respond incorrectly significantly more often when naming long, relative to short low-frequency words, and in Spanish, both groups tended to make significantly more errors while naming long non-words relative to short non-words. The pattern of lexicality effects on naming accuracy was somewhat different. Although the overall lexicality effects on naming accuracy were statistically significant in all languages for both trilingual groups, it is important to note that only in Spanish did participants make more errors in non-word, relative to word naming. In this language, similar to the RT data, the Spanish trilinguals tended to make significantly more errors in long, relative to short non-words, thus showing a significant lexicality effect for long letter-strings. In contrast, the native Hebrew speakers showed the opposite pattern, with a significant lexicality effect for short letter-strings and a non-significant effect for long letter-strings, despite the fact that these participants had also made more errors while naming long non-words relative to short non-words, however, since a relatively large number of errors was made while naming long low-frequency words, the difference between the latter and long non-words was not significant.

In Hebrew and English the mean number of errors made in word trials exceeded that made in non-word trials. These differences were statistically significant for long letter-strings in both groups, since in these languages, long low-frequency words were named incorrectly significantly more often than long non-words. The native Spanish trilinguals also showed a significant lexicality effect for short letter-strings in Hebrew, since a large proportion of errors was made in short low-frequency words as well as long ones in this group.

a. Naming errors in Spanish



b. Naming errors in Hebrew

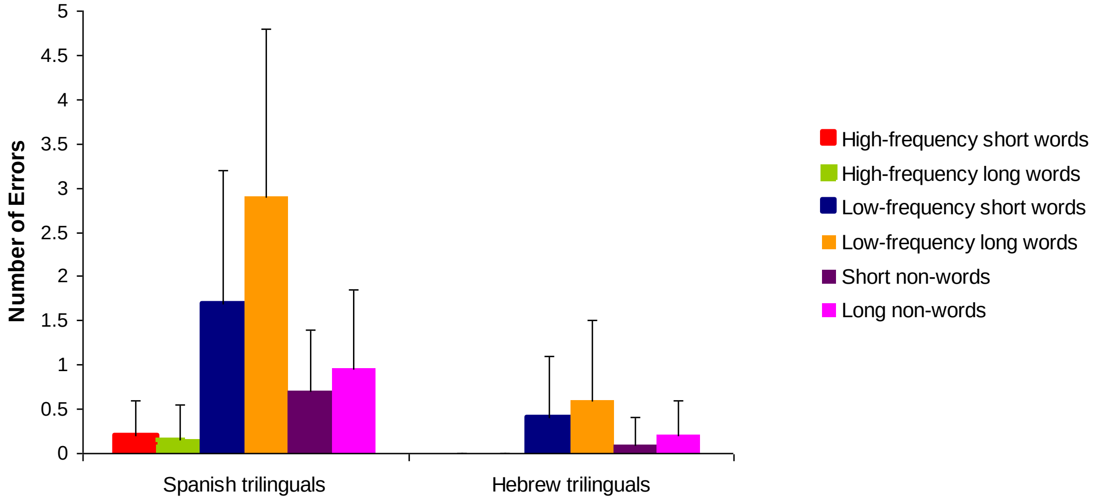


Figure 5-2 *Naming errors in* ***a.*** *Spanish,* ***b.*** *Hebrew,* ***c.*** *English (continued below)*
Error bars represent standard deviations from the mean, as indicated in Table 5-6

c. Naming errors in English

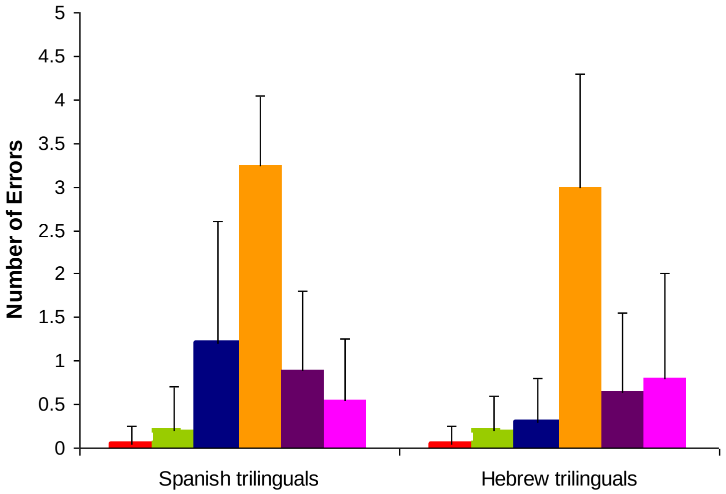


***Figure 5-2** continued*

5.2.3.2.2 Types of errors made in each language

***Table 5-8** Types of errors made by each trilingual group in each language [mean errors (SD)]*

	Spanish Trilinguals			Hebrew Trilinguals		
	Spanish	Hebrew	English	Spanish	Hebrew	English
Stress Assignment	1.65 (2.1)	0.75 (0.7)	0.2 (0.4)	5.75 (3.2)	0.05 (0.2)	0.15 (0.4)
Phonological errors	0.8 (0.7)	4.2 (3.1)	5.35 (2.8)	1.25 (1.6)	0.8 (1.2)	3.35 (1.6)
Lexicalisation	0.35 (0.7)	0.9 (0.9)	0.45 (0.7)	0.3 (0.7)	0.05 (0.2)	0.45 (0.9)
Word Substitution	0.35 (0.9)	0.75 (1.2)	0.1 (0.4)	2.4 (3.1)	0.4 (0.6)	1.05 (1.3)

Types of errors were categorised as:

- *Stress assignment; referring to incorrect assignment of stress of polysyllabic words*
- *Phonological errors; referring to violation of correct phonemic pronunciation of words. In Spanish, these errors could be pronouncing a silent H. In English, these errors can be made predominantly in irregular words e.g. 'gauge', while in Hebrew these errors can be made by assigning an incorrect vowel to a consonant string, e.g. the string GMD (גמד), which should be pronounced as 'gamad' to mean dwarf, could be mistakenly pronounced 'gemed', which has no meaning*
- *Lexicalisation; pronouncing non-words as though they were real words, e.g. 'grink' as drink*
- *Word substitution; errors stemming from swapping the position of letters within words, such as 'beard' and 'bread'.*

The patterns of error-type made by trilinguals in the native languages and in English were identical to those observed by bilinguals in Experiment 1. As seen in Table 5-8 and Figure 5-5, the majority of stress assignment errors were made in

Spanish, with a very small proportion of this type of mispronunciation seen in Hebrew and English. Concordantly, there was a statistically significant association between this type of errors and language in both groups: $\chi^2_{(2)}=22.58$, $p<0.001$ for Spanish trilinguals; $\chi^2_{(2)}=24.87$, $p<0.001$ for Hebrew trilinguals. In contrast, phonological errors were most prevalent in English and Hebrew: $\chi^2_{(2)}=21.27$, $p<0.001$ for Spanish trilinguals; $\chi^2_{(2)}=26.00$, $p<0.001$ for Hebrew trilinguals. In addition, the proportion of lexicalisation errors was consistently small in all languages ($\chi^2_{(2)}=4.61$, $p=0.10$ for Spanish trilinguals; $\chi^2_{(2)}=1.15$, $p=0.56$ for Hebrew trilinguals). Interestingly, the native Hebrew speakers tended to make a relatively large proportion of word substitution errors in all three languages, with the largest proportion found in Hebrew, though no significant association was found between this type of error and language in this group ($\chi^2_{(2)}=3.63$, $p=0.16$). Similarly, the native Spanish speakers showed the highest proportion of word substitutions in Hebrew, with a somewhat smaller proportion in Spanish, and nearly none in English, though the effect was not significant ($\chi^2_{(2)}=3.95$, $p=0.14$).

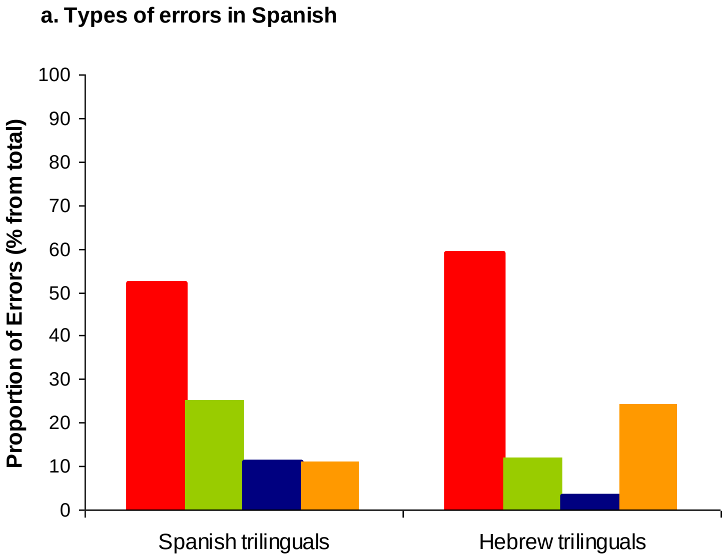
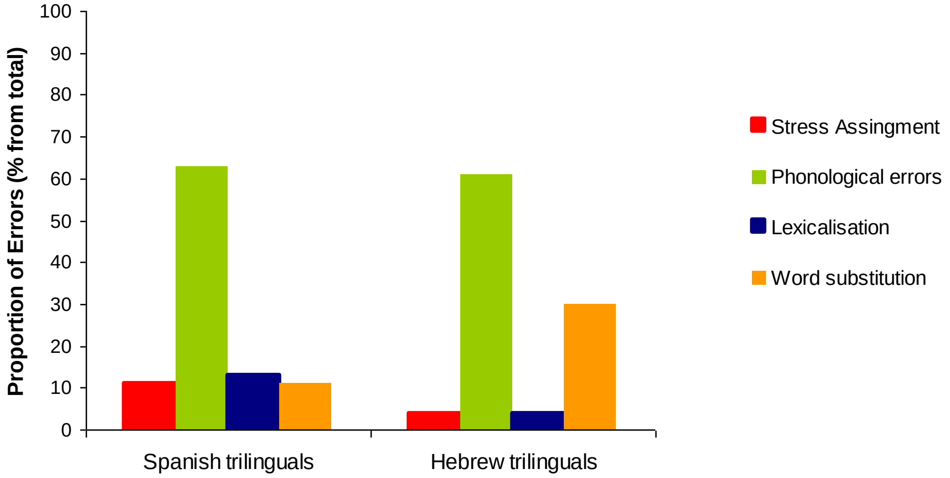


***Figure 5-3** Types of naming errors; **a.** Spanish, **b.** Hebrew, **c.** English (continued below)*

b. Types of erros in Hebrew



c. Types of errors in English

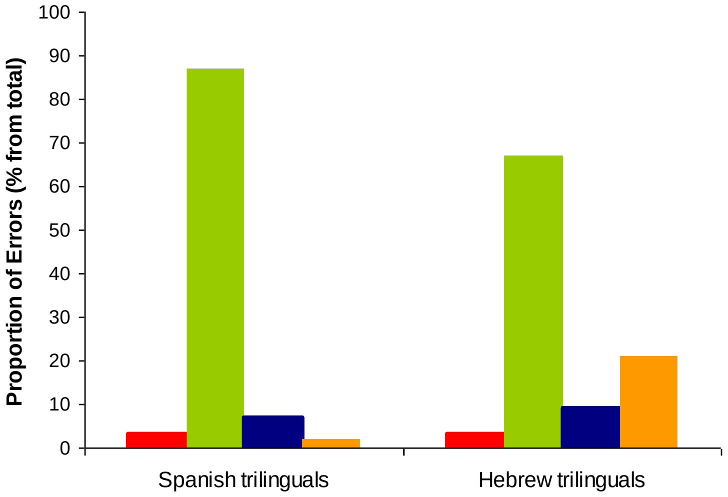


Figure 5-3 *continued*

5.2.4 Discussion

The present experiment assessed the reading strategies employed by two groups of Spanish, English and Hebrew trilinguals; native speakers of Spanish and Hebrew, respectively, using a word / non-word naming task in the three languages.

The experiment was aimed at extending the findings of Experiments 1 and 4, which indicated that reading strategies employed by bilinguals of Spanish and English, and of Hebrew and English, were largely shaped by the varying levels of orthographic transparency in these languages.

The present results showed that each trilingual group exhibited optimal naming performance in the respective native language, while showing similar naming latency trends in all languages, whereby high-frequency words were named faster than low-frequency words, short letter-strings were named faster than long letter-strings and real words were named faster than non-words. All main effects of frequency, length and lexicality were thus statistically significant. The main effects of group, however, were significant only in Hebrew, since native Hebrew trilinguals were consistently faster at naming words and non-words in their native language, relative to the native Spanish trilinguals.

The differences observed in the patterns of interactions between frequency, length and lexicality were in keeping with the levels of orthographic transparency of each native language, and replicated the findings of Experiment 1. Specifically, the native Spanish trilinguals showed a strong modulation of frequency effects by string-length in Spanish, which in turn were strongly modulated by lexicality, as seen by a systematic increase in naming latency between short and long high-frequency words, low-frequency words and non-words. This trend was in the opposite direction in Hebrew, whereby the native readers showed a systematic decrease in length effect between high-frequency words, low-frequency words and non-words. Similarly, in keeping with previous findings (Ellis & Hooper, 2001; Ellis et al, 2004), naming accuracy patterns reflected the orthographic properties of each native language, whereby the highest proportion of errors made in Spanish were related to incorrect stress assignment, while the majority of Hebrew errors were related to phonological mispronunciations, with a somewhat higher proportion of word substitutions, relative to the other languages. In addition, while patterns of frequency, length and lexicality effects on Spanish accuracy mirrored the RT data, Hebrew patterns did not. The majority of errors in Hebrew were made while naming low-frequency words, with very little difference between short and long words. Word-frequency, therefore significantly affected naming accuracy, whereas word-length did not. In addition, lexicality effects on naming accuracy in Hebrew were significant, though this effect was in the opposite direction to that seen in Spanish, since the number of errors made in Hebrew words exceeded that made for non-words. This was due to the absence of written vowels, which permits any combination of spoken vowels to be assigned to a consonant string comprising non-words.

Importantly, Hebrew trilinguals showed a strong length effect for high-frequency words, which gradually diminished as frequency decreased, as also seen by their bilingual counterparts in Experiment 1. This observation lends further support for the ‘strategic dilemma’ proposed in Experiment 2, whereby upon initial exposure to the experimental materials, the cognitive system’s default strategy; phonological assembly (c.f. *Phonological Hypothesis*; Frost, 1994; 1995), interfered with fast lexical retrieval, particularly manifested in Hebrew high-frequency words.

The present patterns observed in English; the midpoint in the orthographic transparency continuum, also corroborated those observed in ESL for the bilingual participants in Experiment 1. Specifically, the native Spanish trilinguals showed a moderate modulation of frequency effects on naming latency by word-length, which in turn was modulated by lexicality, relative to their native, more transparent language. The native Hebrew trilinguals, although overall faster than the native Spanish trilinguals, showed stronger effects of length, particularly for low-frequency words and non-words, indicating a stronger modulation of frequency effects by length, as well as a stronger modulation of length effects by lexicality in English by this group of trilinguals, relative to the native Spanish group. As discussed earlier, these modulations were in the opposite direction to those seen in the orthographically opaque Hebrew.

Naming accuracy patterns in English were largely similar for both trilingual groups, whereby errors were mostly related to phonological mispronunciations, and the majority were made while naming long low-frequency words. The observed effects of frequency and length on real word naming accuracy mirrored the RT data, whereas the effects of lexicality did not. In this case, unlike in Hebrew, the presence of written vowels in English, which permits the correct assembly of any letter-string even in the absence of meaning, led to considerably less errors in non-word trials.

Importantly, the present findings strengthen the argument that the putative ‘compensatory mechanism’ adopted by Hebrew readers for ESL in Experiments 1 and 4 was not related to inferior language proficiency. While the demographic data of participants from Experiment 1 (and 4) suggested that native Spanish bilinguals may have been more proficient in English than native Hebrew bilinguals, demographic details and naming performance in the present experiment showed that native Hebrew trilinguals were more proficient in English than native Spanish trilinguals. However, the differences in the magnitude of interactions between frequency, length and lexicality were replicated in the present experiment.

Admittedly, these differences could have risen as a result of the different scripts, i.e. Spanish readers could have exhibited weaker modulation of frequency effects by length, and of length effects by lexicality than Hebrew readers because Spanish and English carry the same script, which is fundamentally different from Hebrew. However Table 5-2 and 5-3 clearly show that for the native Hebrew trilinguals, naming latencies in Hebrew and English (and indeed in Spanish) were overall very similar, despite the script difference. It is therefore plausible that the Hebrew readers were employing a ‘compensatory mechanism’ for reading in English, whereby in keeping with Frost’s findings (1994; 1995), these participants seized the opportunity to phonologically assemble words when vowels were available, leading to increased length effects for lower-frequency words, in spite of this being an inefficient way to read in English, which may be more transparent than Hebrew, but by all accounts is still a very opaque orthography.

At the same time, Hebrew trilinguals showed a trend towards word substitution errors in English to a greater extent than the Spanish trilinguals, which was also observed by bilinguals in Experiment 1. This trend may point towards some transfer of the strategy employed in the native language to a less dominant language, as seen in the activation patterns produced within certain cortical regions in Experiment 4. Indeed, in the present experiment, a relatively high proportion of word substitutions was also observed while Hebrew trilinguals were reading in Spanish, though this also, was not statistically significant.

The main strength of the present experiment was the ability to compare naming patterns in the three languages, and particularly the two extremities of the orthographic transparency continuum within the same set of participants. While reading in Spanish and Hebrew, both groups showed overall similar patterns of effects of frequency, length and lexicality, in keeping with the level of orthographic transparency of each language. However, some differences emerged between the two groups, which merit particular attention.

First, the demographic details and circumstances of the native Spanish trilinguals suggested that these participants may have been more proficient in Hebrew than in English, since age of acquisition of Hebrew was earlier than that of English, and language exposure through formal education and in daily life was higher in Hebrew than in English. Indeed, at the time of testing, most Spanish trilinguals had been living in Israel for longer than they had in their native, Spanish-speaking countries. Nevertheless, naming performance in this group was superior in English than in Hebrew, and thus seemed to indicate that in fact, Hebrew proficiency was inferior to English in this group. The discrepancy between the demographic data and naming performance in the Spanish trilinguals may be attributed to a greater effort required by these participants to read in the extremely opaque Hebrew, relative to the more transparent English, despite the higher levels of exposure to Hebrew. This notion is in keeping with the findings of Benuck and Peverly (2004), which showed that native English bilinguals exhibited a greater reliance on semantic context when reading sentences in Hebrew relative to English. Moreover, these authors showed that reliance on context was increased when Hebrew words were more ambiguous. Another study that examined reading in Hebrew by non-native English-Hebrew bilinguals was conducted by Gollan, Forster and Frost (1997). Their study assessed the effects of repetition priming within each language, and translation priming across the two languages, using a lexical decision task. Results indicated that in English (L1) – Hebrew (L2) bilinguals and Hebrew (L1) – English (L2) bilinguals alike, repetition priming effects in Hebrew were weaker than in English, which was attributed to the high level of phonetic ambiguity of Hebrew. Moreover, when assessing cross-language translation priming effects with native language primes and second language targets, native Hebrew bilinguals (who were presented with Hebrew primes and English targets) showed moderately enhanced translation priming effect for cognates (53 ms) relative to non-cognates (36 ms), while the native English bilinguals showed a markedly strong enhanced effect in the same direction (142 ms effect for cognates and 52 ms for non-cognates). This “exaggerated” enhanced priming effect (p.1129) was attributed to inferior Hebrew proficiency of native English bilinguals relative to English proficiency of native Hebrew bilinguals. However, when prime-target language was reversed, native Hebrew bilinguals (presented with English primes and Hebrew targets) showed no difference in translation priming effect between cognates and non-cognates (9 ms for both), while English bilinguals (presented with Hebrew primes and English targets) showed a trend for an enhanced effect for cognates (4 ms), and an inhibitory effect for non-cognates (-4 ms), which was even greater in a post-hoc analysis with only proficient bilinguals (-12 ms), indicating that non-cognate primes in Hebrew were interfering with lexical decision, rather than facilitating it. It is therefore likely that the high level of orthographic opacity of Hebrew may have contributed to this interference to a greater extent than language proficiency. However, it is important to note that both studies descried above demonstrated significant effects of language exposure on performance. Benuck and Peverly (2004) showed that participants regarded as the less advanced readers relied on semantic context in Hebrew to a greater extent than the more advanced readers. Similarly, Gollan et al (1997) showed that lexical decisions in Hebrew non-word trials were considerably slower for bilinguals tested in the USA, relative to bilinguals tested in Israel. These findings emphasise the important role of language exposure in fluent reading, in addition to level of orthographic transparency. In the present study, correlation analysis showed significant relationships between language exposure in Spanish trilinguals and naming performance in Hebrew, suggesting that inferior proficiency also contributed to slower naming in Hebrew.

For the native Hebrew trilinguals, demographic details showed that these participants had lived in Spanish-speaking countries longer than in English-speaking countries, while age of acquisition and formal education in Spanish and

English were similar. However, subjective rating of language exposure in daily life was greater in English than in Spanish and indeed, in this group of participants naming performance in English exceeded that observed in Spanish. Moreover, naming accuracy in both languages was significantly related to length of residence in Spanish and English-speaking countries, respectively, while English accuracy level was higher. In this case, the higher performance in English relative to Spanish is likely to be related mainly to language exposure. This may be surprising, particularly to advocates of script effects, since high proficiency in English is also likely to be manifested in faster reading of Spanish words and non-words, given its high level of orthographic transparency.

Second, a point which transpires from the arguments above is the similarity in Spanish naming latencies for short words and non-words between the two groups. As illustrated in Figure 5-1, the differences between the groups emerged in long letter-strings, whereby the native Hebrew readers were considerably slower. Indeed, a close examination of the data revealed that among the items that elicited the slowest RTs were the words *acanto, genoma, hocico, secuaz,* and the non-words *dopite, obchol, gepilo* and *ñarpil*, for which correct pronunciation requires knowledge of the stress assignment rules. Interestingly, 6 of these items also elicited slower RTs in the native Spanish group. However, other words, such as *bípedo* and *pábulo*, for which the accent mark was present, indicating to the reader the syllable to be stressed, also elicited slower RTs in the Hebrew group. Therefore in the case of Hebrew trilinguals reading in Spanish, it is not possible to rule out the suggestion that slower naming was related to inferior language proficiency, however, it is also plausible that given the opportunity to phonologically assemble words with the aid of written vowels, these readers resorted to the ‘compensatory mechanism’, which was manifested in this transparent language to a greater extent than in the ‘quasi transparent’ English. Examining this issue in a group of highly proficient Hebrew-Spanish bilinguals in a future experiment would help support this assertion further.

Third, in Hebrew trilinguals, length and lexicality effects on naming latency of Spanish non-words were stronger for short relative to long items. This was also seen in the naming accuracy data, and was attributed to a large proportion of low-frequency words being perceived as non-words in Spanish. Similarly, the slower naming of Hebrew long low-frequency words by Spanish trilinguals was attributed to the perception of a large proportion of low-frequency words as non-words, stemming from lower Hebrew proficiency, as suggested by the significant correlation between naming latency of these words and formal education in Hebrew. In both cases, the slower naming of long low-frequency words resulted in group differences in the patterns of interaction between frequency and length in Hebrew, and length and lexicality in Spanish. Perhaps a more pragmatic approach would have been to expose participants to the experimental stimuli prior to the experiment and alert them to the presence of non-words. This was not done due to concerns of significantly reducing frequency and lexicality effects through prior exposure to the items, however, this consideration might be useful for future experiments, based on the findings of the present study.

Taken together, the present experiment exemplified the complexity involved in the interpretation of data obtained from multilinguals, due to the varying levels of language exposure and context of language-use (Grosjean, 1989). However, despite the differences observed between the two trilingual groups, the overall trends in the three languages were similar, whereby both groups showed strong modulation of frequency effects by length in Spanish, moderate modulation in English, and an inverse modulation in Hebrew, in keeping with the graded levels of orthographic transparency of these languages. In addition, both groups showed similar patterns of naming accuracy, whereby the majority of errors made in Spanish were related to incorrect stress assignment, whereas the majority of errors made in English and Hebrew were related to phonological mispronunciations of real words. Importantly, while there was a trend, hinting towards a certain degree of transfer of the native strategy to the less dominant languages in Hebrew readers, the combined findings of the present experiment lend further support to the proposed ‘compensatory mechanism’ employed by these readers when faced with a relatively more transparent orthography than their native language, particularly in English. In the case of Spanish, the present data may point towards a stronger compensatory mechanism relative to English, though the effects of language proficiency cannot be ruled out in the present experimental sample. Further research is thus required in order to strengthen this novel finding. The final chapter of the thesis outlines discusses the implications of the present study, its limitations and suggestions for future research.

Chapter 6

Conclusion and Implications

The present study examined the cognitive processes and neural correlates of reading strategies employed by bilingual and trilingual readers of three languages, whose writing-systems can be viewed as placed along a continuum of orthographic transparency, with Spanish at the transparent extreme, Hebrew at the opaque extreme and English as the midpoint. This is the first study to combine behavioural measures and neuroimaging to address the combined effects of orthographic transparency and language proficiency in these three languages.

Since the early 20th century, studying the cognitive processes underlying literacy and multilingualism has been the goal of several disciplines, aiming to understand the cerebral architecture of multiple-language processing, to develop teaching methods and remedial interventions for dealing with reading impairment in different languages, or to satisfy some of humanity's best traits; curiosity and aspiration for knowledge. The findings of the five experiments reported in the present study carry implications pertaining to all of the above. This final chapter summarises the main findings of the present study, outlines its limitations and scope for future research and ponders upon its implications in light of the questions put forward in Chapter 1.

6.1 The effects of the graded levels of orthographic transparency of Spanish, English and Hebrew on reading strategies employed by native readers

Experiment 1 assessed the effects of word-frequency, length and lexicality on naming latency and accuracy in the three languages, in bilinguals of Spanish and English, and Hebrew and English, as compared to English monolinguals. Naming accuracy results reflected the orthographic properties of each language, whereby Spanish errors were primarily related to incorrect stress-assignment, occurring most often while naming long non-words, whereas English and Hebrew were associated primarily with phonological mispronunciations of real words, made mostly during low-frequency word naming. These findings are in keeping with previous studies assessing the effects of orthographic transparency on naming performance (Ellis and Hooper, 2001; Ellis et al, 2004). Concurrently, the strong effects of frequency, length and lexicality on naming latency in the native languages were indicative of reliance on lexical / semantic processing as well as sublexical / phonological processing in all three languages, though the observed patterns of interactions between these effects demonstrated that the interplay between the types of processing varied in accordance with the orthographic properties of each language, and in keeping with the weak version of the Orthographic Depth Hypothesis (Katz & Frost, 1992). Specifically, frequency and lexicality effects were strongly modulated by string-length in Spanish, somewhat less so in English, and inversely modulated in Hebrew. Moreover, in the latter, the absence of written vowels led to robust lexicality effects and minute length effects for non-words. Interestingly, the inverse interactions between frequency, lexicality and length stemmed from an unusually strong length effect for high-frequency words, which gradually diminished as frequency of items decreased. Experiment 2 conducted in Hebrew only, confirmed that this effect was related to slower processing of long letter-strings in these readers. This observation was therefore best accounted for within a Dual-Route framework, whereby upon initial exposure, readers attempted sequential assembly of experimental stimuli, which conflicted with the optimal strategy for this opaque orthography; fast lexical retrieval. This finding lends support to the Phonological Hypothesis (c.f. Frost, 1994; 1995), suggesting that the default strategy of the cognitive system is sequential assembly of written material, giving way to lexical processing when this constitutes a more efficient way for visual word recognition. The conflict between sequential assembly and lexical retrieval seen in these readers was therefore referred to as a ‘strategic dilemma’. Interestingly, in Experiment 1, while the effects of this dilemma were most evident in Hebrew, they were somewhat less evident in English, and not at all in Spanish, where the high level of orthographic transparency of this language permits correct sequential assembly of words and non-words, thereby reducing the conflict between lexical and sublexical routes.

Taken together, the findings of the first two experiments replicated and extended the findings from the initial cross-language study conducted by Frost, Katz and Bentin (1987), and thus demonstrated that reading strategies employed by native readers were largely constrained by the level of orthographic transparency of their native languages, in keeping with subsequent findings (Paulesu et al, 2000) and observations of differentially manifested symptoms of dyslexia in different languages (e.g. Wydell & Butterworth, 1999; Beland & Mimouni, 2001).

6.2 Visualising the different types of strategies involved in reading Spanish, English and Hebrew at the cortical level

The first fMRI experiment (Experiment 3), albeit a preliminary experiment, conducted with three participants; one from each target population, confirmed the suitability of the chosen experimental design for a bilingual comparison of reading strategies in Spanish, English and Hebrew. The second fMRI experiment (Experiment 4), therefore set out to visualise the neural correlates of the effects observed in Experiment 1, and clarify the outstanding issues which arose in the latter. Results showed that reading in all three languages was mediated by a distributed network of largely overlapping regions, also involved in spoken language processing, in accordance with previous neuroimaging studies (Pugh et al, 1996; Fiez et al, 1999; Wydell et al, 2003; McDermott et al, 2003; Joubert et al, 2004; Klein et al, 1994; D'esposito & Alexander, 1995; Kim et al, 1997; Deahaene et al, 1997; Yetkin et al, 1996; Chee et al, 1999; Pu et al, 2001; Hernandez et al, 2000; Paulesu et al, 2000; Hernandez et al, 2001; Vingerhoets et al, 2003; Briellmann et al, 2004; Meschyan & Hernandez, 2005; Halsband, 2006), while reading in each language was also associated with some preferential patterns of activation, which were in keeping with their graded levels of orthographic transparency. Specifically, reading in Hebrew was associated with activation within the triangular part of the left inferior frontal gyrus, whereas reading in Spanish was associated with activation in the opercular portion, while reading in English was associated with activation within both portions of the gyrus. Similarly, reading in Spanish led to activation within the left postcentral gyrus, not seen in the other native languages. In addition, Spanish and English, but not Hebrew, were associated with activation in the left inferior parietal lobule, whereas Hebrew and English, but not Spanish, were associated with activation within the left middle frontal gyrus. Moreover, the spatial extent of activation within the right occipital cortex varied systematically between the languages, in keeping with their positions along the orthographic transparency continuum. These observations corroborate previous findings demonstrating the effects of orthographic transparency of different languages on the patterns of cortical activation (Paulesu et al, 2000; Meschyan & Hernandez, 2005; Simon et al; 2006; Mechelli & Price, 2005; Balota & Yap, 2006).

Further support for this assertion stemmed from the patterns of effects of frequency, length and lexicality and interactions between them, observed within regions of interest. The robust length effects in Spanish within all ROIs were indicative of strong reliance on phonological processing, whereas the absence of these effects in Hebrew, coupled by significant frequency and lexicality effects were taken as evidence for predominant reliance on lexical processing in this language. Moderate length effects in English and significant frequency and lexicality effects suggested a more balanced interplay between the different types of processing. In addition, observed length effects in the occipito-temporal cortex in Hebrew were taken as further evidence for the strategic dilemma faced by these readers while reading in their native language. Interestingly, the patterns of signal change between the different conditions within the medial frontal gyrus, implicated in attentional, rather than linguistic processing (Price, 2000; Fernandez-Duque & Posner, 2001), exemplified the acute complexity of reading in Hebrew, the relative simplicity of reading in Spanish and the intermediate position of English in the continuum. The patterns of cortical activation in the native languages thus supported the behavioural results of Experiment 1.

In addition, the findings of the fMRI experiments strengthened the functional distinction between the opercular and triangular portions of the left inferior frontal gyrus, lent further support to the implication of the inferior parietal cortex in phonological processing and demonstrated that the left fusiform gyrus, previously shown to be involved in the processing of visual word forms, was also sensitive to effects of word-frequency and length. Moreover, the present results suggested that the homologous fusiform gyrus, typically referred to as the fusiform face area, also plays a role in reading, and furthermore, it is sensitive to orthographic transparency. Since the role of this region in language processing has been rather overlooked, this latter finding emphasises the importance of paying particular attention to this region in future studies, and considering its role in the manifestation and recovery patterns of acquired reading disorders. This point will be expanded on in section 6.6.

6.3 The effects of the orthographic properties of the native language on the reading strategies employed in a second and third language

The question of the effects of the orthographic properties of the native languages on the strategies employed by readers in their second and third languages was fuelled by suggestions of transfer of strategy from the native language to less dominant languages (Muljani et al, 1998; Wang et al, 2003), which although intuitively logical, has been somewhat controversial (Akamatsu, 2002; Lemhöfer et al, 2008). In Experiment 1, while both groups of bilinguals showed the expected effects of language proficiency with slower naming and lower accuracy level relative to their native language, there was little, if any evidence for a transfer of strategy from the native languages to ESL. In fact, both groups exhibited an adaptation of the reading strategy to the level of orthographic transparency of English. The observed patterns of interactions between frequency, lexicality and length in the native Spanish readers suggested a reliance on lexical processing to a greater extent in the less transparent language, while the patterns observed in the native Hebrew readers suggested a greater reliance on phonological processing in this, *more* transparent language. Interestingly, the reliance on phonological processing in ESL by the native Hebrew readers appeared to be greater than that seen for their native Spanish counterparts, and was proposed to occur as a result of an exaggerated reliance on phonological assembly, whereby, faced with a relatively more transparent language, these readers seized the presence of written vowels as an opportunity to rely on sequential assembly of written material, at the expense of naming speed. This proposal is in keeping with the findings of Frost (1994; 1995), who compared the extent to which Hebrew readers relied on phonological processing when presented with vowelised Hebrew words. However, as a novel observation, the data obtained from Experiment 1 was necessary, but not sufficient to validate this theory.

Parallel to the slower naming and lower level of accuracy in ESL observed in Experiment 1, results of both fMRI experiments demonstrated language proficiency effects, reflected in the spatial extent and intensity of activation, particularly within the medial frontal cortex, as well as in specific activation within the right precentral, inferior frontal and middle temporal gyrus. These observations are in keeping with previous bilingual and multilingual studies demonstrating increased cognitive demand for the processing of a second language (Perani et al, 1996; Dehaene et al, 1997; Kim et al, 1997; Hernandez et al, 2001; Wattendorf et al, 2001; Proverbio et al, 2002; Watenburger et al, 2003; Vingerhoets et al, 2003; Pillai et al, 2003).

Importantly, both bilingual groups showed activation within largely overlapping regions within the left hemisphere, with marked differences between ESL and each native language, indicating that native Spanish and native Hebrew readers alike had adapted their reading strategies to the level of orthographic transparency of English. At the same time, Experiment 4 showed subtle differences between the groups in the anatomical patterns of activation, whereby more anterior regions of the left IFG were activated by the native Spanish bilinguals, whereas activation in more posterior regions of the inferior frontal cortex was detected in the native Hebrew bilinguals. This observation suggests that the Hebrew bilinguals relied on phonological processing while reading in ESL to a greater extent than their native Spanish counterparts, and further strengthens the notion of an exaggerated reliance on phonological assembly by these readers. This was corroborated by the patterns of effects of frequency, length and lexicality observed within the medial frontal gyrus, left inferior frontal gyrus, right middle temporal gyrus and right fusiform gyrus. However, the effects observed within the other ROIs, namely left precentral gyrus, left inferior parietal lobule, left postcentral gyrus and bilateral occipital cortex were indicative of the opposite pattern, whereby the Spanish readers were relying on phonological processing to a greater extent than their native Hebrew counterparts. This latter finding suggests that some degree of transfer of the native strategy to reading in ESL may have also taken place, as suggested by Muljani et al (1998) and Wang et al (2003), though in the present study, the adaptation to the level of orthographic transparency of English was more robust, and ultimately most apparent in the behavioural data.

Taken together, the observed patterns of behavioural naming performance and cortical activation in ESL indicated that while language proficiency had a significant effect on the recruitment of attentional processing, its effect on linguistic processing was less robust, in keeping with recent findings reported by Meschyan and Hernandez (2005). Notably, the proposed exaggerated reliance upon phonological processing by Hebrew bilinguals was strengthened by the observed patterns of cortical activation. Nevertheless, being a 3-point comparison, the present findings called for a trilingual experiment in order to complete the picture. Experiment 5 was therefore conducted in Israel, with two trilingual groups, native speakers of the two extremities of the orthographic transparency continuum; Spanish and Hebrew, respectively, with English as a common additional language.

Results of the final experiment replicated those obtained in Experiment 1 for each group's native language, as well as English as a non-native language, and once again, showed that while native Spanish readers efficiently adapted their reading strategy to the lower level of orthographic transparency of English, the native Hebrew readers resorted to an exaggerated reliance on phonological processing for reading in English, which is more transparent than their native language.

The most interesting findings of the final experiment were the observed naming patterns in the two extremities of the orthographic transparency continuum by non-native readers. While reading in Hebrew, the native Spanish trilinguals were forced to adapt their strategy to the extreme opacity of Hebrew, which came at a considerable cost to reaction time. This finding was in keeping with previous studies assessing reading in Hebrew as a non-native language (Gollan et al, 1997; Benuck & Peverly, 2004), and exemplified the complexity involved in reading in a language which carries no written vowels. Interestingly, while reading in Spanish, the native Hebrew trilinguals showed an adaptation to the high level of transparency of Spanish, though the exaggerated reliance on phonological assembly, which was expected to emerge in Spanish to a greater extent than English was not clearly dissociable from the effects of language proficiency in the present experimental sample. As mentioned in Chapter 5 and discussed in section

6.6, future experiments are required in order to strengthen this observation in Spanish.

6.4 Accounting for existing theories for reading in languages with different orthographic properties

Throughout the thesis the most prevalent theoretical framework has been the weak version of the Orthographic Depth Hypothesis (Katz & Frost, 1992), derived from its predecessor, the strong version (Frost, Katz & Bentin, 1987), which in turn, was based on the Dual-Route model for reading (Coltheart & Rastle, 1994; Rastle & Coltheart, 1998). As outlined in Chapter 2, this model postulates the existence of two primary mechanisms for reading; the sublexical / phonological route and the lexical / semantic route, which operate in a parallel and competitive fashion to generate pronunciation of printed material. Indeed, the current findings have been discussed within a framework of reliance on phonological assembly, and / or lexical retrieval via access to semantics, whereby reading in Spanish was shown to be achieved primarily (though not exclusively) via phonological assembly, whereas reading in Hebrew was shown to be achieved primarily (but not exclusively) via lexical processing through access to semantics, while reading in English was shown to involve a rather balanced interplay between the two routes. Similarly, the strategic dilemma seen primarily in Hebrew was described as an initial activation of the phonological route, which interfered with the more efficient means for reading in Hebrew; the lexical route, particularly while reading high-frequency words. This observation also lent support to the Phonological Hypothesis (Frost, 1994; 1995), suggesting that the default strategy of the cognitive system, regardless of orthographic transparency, is initial phonological assembly. At the same time, the Dual-Route model implies that reliance on the lexical route tends to increase with reading experience, whereby a larger proportion of words may be perceived as frequently encountered. Experienced readers may thus resort to the faster lexical route even in transparent orthographies such as Spanish, and therefore language proficiency effects seen in the present study were attributed to greater reliance on the phonological route, particularly during exposure to low-frequency words and non-words, more so when they were long than short. Consequently, the exaggerated use of phonological processing in ESL seen in Hebrew bilinguals and trilinguals were initially plausibly attributed to inferior language proficiency of these readers. However, having ruled out this possibility, this observation was attributed to a ‘compensatory mechanism’ employed by these readers, whereby an exaggerated reliance on the phonological route stemmed from the relative ease with which reliance on written vowels can aid pronunciation of less frequently encountered words, relative to the complexity of directly retrieving the representation of this type of words from the mental lexicon with little or no phonological information, as is the case in Hebrew. Not surprisingly therefore, this compensation was manifested to a greater extent for long letter-strings relative to short ones.

It therefore seems that the present findings can be comfortably accounted for in light of a Dual-Route framework, though some observations in the present study could also be explained in light of alternative models. For example, the Parallel Distributed Connectionist reading model, which postulates a single mechanism for reading all types of words, based entirely on reading experience (Seidenberg & McClelland, 1989; Plaut et al, 1996; Plaut & Kello, 1998), could account for the effects of orthographic transparency on naming performance in terms of strength of weighted connections between orthography and semantics in Hebrew, as opposed to stronger connections between orthography and phonology in Spanish. Similarly, this model could account well for the language proficiency effects. However, the strategic dilemma and exaggerated reliance on phonological assembly have been proposed to arise through a conflict between the most efficient reading strategy and the more comfortable one, which could only be accounted for by the existence of two parallel mechanisms.

An alternative theory which could better account for the present findings is a relatively recent theory, proposed as an improved and modern alternative to the Orthographic Depth Hypothesis (Frost, 2006); the Psycholinguistic Grain Size Theory (PGST; Ziegler & Goswami, 2005), derived from the Hypothesis of Granularity and Transparency (Wydell & Butterworth, 1999). ‘Grain size’ refers to the size of linguistic units that constitute a building block of a word. The smallest grain unit in alphabetic languages is the grapheme, though the average grain size in a given language increases as its level of orthographic transparency decreases. Based on this concept, reading in transparent languages such as Spanish may involve the processing of small grain units at the graphemic level; reading in opaque languages such as English may involve small, as well as larger grain units, such as grapheme clusters and morphemes, while reading in Hebrew involves predominantly large grain units, namely at the morphemic level. The PGST therefore provides a continuous measure of linguistic units, rather than the dichotomous concept of lexical or sublexical routes. Within this framework, interactions between frequency and length may therefore arise as a result of the processing of low-frequency words via reliance on smaller grain units, whose number inevitably increases in longer letter-strings, giving rise to length effects. Similarly, the ‘compensatory mechanism’ seen by Hebrew readers in ESL could arise from the preference of these readers to rely on smaller linguistic units, which is not permissible in Hebrew. Moreover, the slower naming in Spanish long letter-strings seen by Hebrew trilinguals can therefore be explained by the smaller grain units relied upon in Spanish relative to English, and can thus point towards a stronger ‘compensatory mechanism’ in the most transparent language of the continuum. A proposal for a future project could be to create a database of words with average grain size units, similar to already collected measures of frequency of occurrence, neighbourhood size and imageability. At present however, the PGST is used primarily to account for trends in reading acquisition and incidence of developmental reading disorders (e.g. Ziegler & Goswami, 2005; 2006; Goswami, Ziegler & Richardson, 2005; Katz, Lee, Tabor, Frost et al, 2005; Nikolopolous, Goulandris, Hulme & Snowling, 2006; Martens & De Jong, 2006; Burani, Marcolini, De Luca & Zoccolotti, 2008; Sun-Alperin & Wang, in press), some of which will be discussed in section 6.7.

6.5 Limitations of the present study

As with any multilingual study, the key limitation in the present study stemmed from the difficulty in gathering a group of participants who would be identically matched for language proficiency. As can be noted in the demographic details of bilingual and trilingual participants, age of acquisition, length of residence, time of formal education and subjective rating of exposure to each language varied considerably. Indeed, in the trilingual sample there were significant group age differences, which needed to be minimised with statistical manipulation. Unbalanced multilingualism is likely to have contributed to the difficulty in dissociating between the effects of language proficiency and orthographic transparency.

This problem may have been circumvented with the inclusion of explicit proficiency measures such as standardised language proficiency tests, which could have provided a more stringent measure of language proficiency than the naming accuracy data. These were not used in the present study due to two major concerns. First, the heterogeneity of standard proficiency tests in each of the three languages examined in the study would have posed a difficulty in determining assessment criteria which would be equivalent for each language. Second, requesting participants to complete a language proficiency test would have rendered the experimental procedure extremely lengthy, particularly for trilingual participants, and might have discouraged participation and compromised performance.

Another limitation of the present study concerns the choice of words for experimental trials. While these were carefully selected to be matched for frequency, length and initial phonemes, other factors, such as imageability and subjective familiarity might have influenced reaction time and thus might have contributed to the variability in the spread of the data. Collecting words from various databases and matching them for the various linguistic factors, particularly in several languages yields a very limited list of words. Indeed, in the present study a relatively large proportion of trials were discarded due to considerably slow reaction times and inaccuracy. At the time the experiments were being constructed the availability of databases in Spanish and Hebrew was poor, and none included factors other than frequency of use. In recent years however, the availability and scope of word databases in different languages have improved considerably, which will, no doubt prove beneficial for future studies.

In that vein, an additional limitation, relevant specifically to the Spanish experiment, relates to the fact that participants were nationals of several Spanish-speaking countries. Though care was taken to include words which were universal to the Spanish-speaking population, the Spanish spoken in Spain varies considerably from that spoken in Latin America, and within the latter large variations exist as well. It is therefore plausible that some low-frequency words may have been perceived as non-words by some participants, which might also contributed to the variability in the data. While most bilingual and multilingual studies have included participants from homogeneous nationalities, this was not feasible in the present study, due to the difficulty in recruiting participants who were proficient in the three languages under investigation, particularly trilinguals residing in Israel. Nonetheless, the patterns of frequency, length and lexicality effects observed in the behavioural data, and the patterns of activation observed in the neuroimaging experiments were robust and strongly suggestive of assembled phonology as the prevalent strategy for visual word recognition in Spanish, relative to English and Hebrew.

6.6 Scope for future research

Further experiments which could strengthen the present findings may utilise more specific tasks than the straightforward naming employed presently. For example, the semantic priming experiment conducted by Frost, Katz and Bentin (1987) could be replicated with bilinguals of Spanish and English and Hebrew and English, and / or trilinguals. As described in Chapter 2, these authors had found strong semantic priming effects in Hebrew, moderate effects in English and no effects in Serbo-Croatian. In bilinguals, stronger semantic priming effects in ESL by Spanish readers and weaker effects by Hebrew readers would provide evidence for an exaggerated reliance on phonological processing by the latter group. Importantly, conducting this type of experiment using fMRI could support the behavioural patterns, replicate the present observations in the right fusiform gyrus and shed light on its role in reading, as well as clarify the issues regarding the involvement of specific regions within the right temporal and frontal cortex in second and third language processing. An experiment of this sort has been designed and data collection had commenced, though not completed for inclusion in this thesis.

Additional experimental paradigms could also include a phonological task such as masked phonological cognate priming, similar to that used in Gollan et al's (1997) study. In this case, the compensatory mechanism in ESL would be evidenced by stronger cognate effects in native Hebrew bilinguals relative to Spanish bilinguals. Furthermore, the present study could be replicated with native speakers of other languages whose levels orthographic transparency can be viewed as placed along a continuum, such as Finnish or Italian at the transparent extreme, Arabic, Japanese Kanji or Chinese at the opaque extreme, and English as the midpoint.

Another way to extend the present study could be the use of newly emerging MRI-compatible EEG (Lemieux, Salek-Haddadi, Josephs et al, 2001; Mullinger, Brookes, Stevenson, Morgan, & Bowtell, 2008). Combining these two neuroimaging methods can be extremely beneficial as it enables the precise visualisation of neural correlates of cognitive processes as well as their time-course simultaneously. For the extension of the present study, showing ERP amplitudes reflective of phonological processing in Hebrew bilinguals while reading in English to a greater extent than in Spanish bilinguals could, for example clearly demonstrate the exaggerated use of phonological recoding in these readers while reading in relatively transparent languages.

Indeed there are several ways to replicate and extend the present study, and the more advances are made in neuroimaging technology, the more feasible it becomes to conduct more efficient experiments, to include larger experimental samples, to simplify processes of data analysis and obtain a more detailed picture of reading processes in multilinguals.

6.7 Beyond the present study: thoughts on teaching methods and remedial interventions for developmental and acquired reading disorders

It is well established in the literature that beginner readers of all languages tend to rely primarily on phonological recoding, which gradually gives way to lexical processing with increased reading experience (Wagner & Torgesen, 1987; Share, 1995; Ellis et al, 2004; Ziegler & Goswami, 2005). It is therefore not surprising that as mentioned in Chapter 2, the rate of literacy development in different languages may vary in keeping with their level of orthographic transparency (Thorstad, 1991; Caravolas & Bruck, 1993; Goswami, Porpodas & Wheelwright, 1997; Goswami, Gombert & de Barrara, 1998; Frith, Wimmer & Landerl, 1998; Ellis & Hooper, 2001; Seymor, Aro & Erksine, 2003). Nevertheless, despite the slower rate of literacy acquisition in languages of opaque orthographies relative to transparent ones, it has also been shown that once literacy is established, regular readers of transparent and opaque orthographies alike achieve comparable fluency and accuracy levels (e.g. Seymor et al, 2003; Hanley, Masterson, Spencer & Evans, 2004), and as seen in the present and previous studies, in adulthood, the differences in levels of orthographic transparency constrain the predominant strategy used by skilled readers (e.g. Frost, Katz & Bentin, 1987; Tabossi & Laghi, 1992; Paulesu et al, 2000; Ziegler et al, 2001; de Groot et al, 2002; Meschyan & Hernandez, 2005; Simon et al, 2006). This knowledge bears particular importance for the type of methods used for reading instruction in languages of opaque orthographies such as English and Hebrew. At present, the most widely used teaching approach is phonics training, which has recently been re-implemented following heated public debates in the mid 20th century, among educators, cognitive scientists and policy makers.

6.7.1 The Reading War

These debates received vast media coverage particularly in the USA, where a deep controversy, referred to as the “Reading War” (e.g. Rymes, 2003), raged between the proponents of two principal schools of thought. At one extreme lay the traditional approach, which emphasised the importance of phonemic decoding skills, based on direct instruction of the alphabetic code and phonetic translation of letters to their corresponding sounds. This phonetic approach attested that the basic components of a word, consonants and vowels, were the building blocks of written language and as such, teaching children to read must be based upon this principle. At the other extreme lay a modern school of thought; the “whole-language” approach, derived from the progressive educational stream which soared in the USA in the 1960’s and 70’s. Propounders of the alternative view suggested that decomposing written language into its building blocks did not convey the true purpose of written language: *meaning*. The philosophy of this approach was based largely on the need to reform the traditional and dour education system of that period through an emphasis on children’s rights, individual learning pace, motivation and self-esteem. This whole-language approach compared reading acquisition in young children to the natural and instinctive way in which infants acquire verbal language. Therefore, the basic premise of the new approach predicted that given proper motivation, many opportunities to read, access to good literature, and focus on meaning, reading instruction could be more successful if strategies used meaning clues in the context of real text to help determine the pronunciation of unknown words. By the same token, difficulties in reading acquisition may stem from boredom or lack of motivation, rather than an underlying cognitive deficit, and therefore any attenuation in reading acquisition must be met with tolerance.

Since the whole-language approach stands in stark contrast to the principle of focussing on individual grapheme-phoneme correspondence, the intense debates gave rise to a series of Congressionally-commissioned panels and government-funded reviews of the state of reading instruction in the USA. The “Reading War” climaxed in the last decade of the 20th century, following the accumulation of evidence of severe failure in reading comprehension, particularly in states where education systems had ardently adhered to the whole-language approach. This led to the most comprehensive Congressionally-commissioned report compiled thus far, by a panel convened by the director of the National Institute of Child Health and Human Development (NICHD) in consultation with the Secretary of Education. The panel, comprised of 14 senior investigators in the field of literacy instruction reviewed a corpus of ca 100,000 publications of empirical studies, published their report in 2000. The results of the meta-analysis (Ehri, Nunes, Stahl & Willows, 2001) indicated that several skills were required for successful reading acquisition, among which were phonics, fluency, vocabulary and comprehension. Moreover, the report highlighted that reading was not a naturally occurring phenomenon as verbal language, but a function which requires purposeful and integrated teaching, and showed that 25%-30% of school-aged children in the USA encountered difficulties in its acquisition. According to the empirical literature, reading acquisition problems may stem to a great extent from poor understanding of the alphabetic code, problems in decoding skills and lack of phonological awareness, as well as poor knowledge of semantics, syntax and logic, and indeed lack of motivation in children, in addition to inadequate teacher training. The panel therefore concluded that phonics training, in particular phonological awareness, and systematic instruction of decoding skills and the alphabetic code could significantly improve reading acquisition and subsequently comprehension in children from kindergarten through to 6th grade. Moreover, the direct instruction of decoding skills may be particularly beneficial for children who encounter difficulties in learning to read. The conclusions of the panel thus ended the reading war in the USA, and led to an implementation of phonics as a fundamental aspect of any curriculum for reading instruction.

In the UK, the polemical issue of whole-language versus phonics followed a parallel path over the same time-period, though this was less polarised and involved fewer empirical studies. In 1998, the introduction of the National Literacy Strategy in English primary schools marked the beginning of the return of phonics to the curriculum of reading instruction in the UK. A House of Commons Education and Skills Committee report published in 2005 indicated that in 1997, 67% of 11 year-old children exhibited the expected reading level for their age, a figure which rose to 83% by 2004, thanks to the introduction of the scheme. In 2006, a systematic review of empirical literature on the use of phonics in the UK, commissioned by the department of Education and Skills (Torgerson, Brooks & Hall, 2006) showed that systematic phonics instruction within a broad literacy curriculum was associated with better progress in reading accuracy of children between the ages of 5 and 11 years. Moreover, there was no significant difference in reading accuracy levels between regular readers and those at risk of reading failure. The report thus concluded that "since there is evidence that systematic phonics teaching benefits children's reading accuracy, it should be a part of every literacy teacher's repertoire and a routine part of literacy teaching, in a judicious balance with other elements" (p. 49).

A similar case was seen in the policy of reading instruction in Israel. In the early 1980's the Ministry of Education adopted a policy of promoting whole-language as an efficient method for reading acquisition. In national surveys performed in the late 1990's for the Parliament Reading Committee Report (Shapira et al, 2001) it was revealed that 60% of primary school teachers had adopted this teaching strategy, and as a result, between 48.5% and 25% of year-4 children (aged around 10 years), classified into the lowest and highest socioeconomic bands, respectively, had failed to reach minimal scores in reading comprehension. Following the Shapira Report, however, reforms have been made to encourage the return to phonics. Consequently, the recent Progress in International Reading and

Literacy Study (PIRLS) survey[24] reported that among the Hebrew-speaking year-4 pupils in Israel, the mean reading achievement scale score had increased from 538 in 2001 to 548 in 2006; a 10-point increase which was reported as statistically significant (Israeli Ministry of Education: http://rama.education.gov.il).

It is therefore now widely accepted that providing phonological decoding skills and training phonological awareness are key components in successful reading acquisition. In the UK at present, the National Literacy Strategy, which in 2003 merged with the related numeracy strategy to become part of the Primary National Strategy (http://www.standards.dfes.gov.uk/primary/), focuses on promoting high standard of teaching through a rich and varied curriculum, based on the pedagogic principles of the propounders of the whole-language approach, and the methodological principles of the phonetic approach, supported by empirical research from linguistic and psycholinguistic studies.

6.7.2 Developmental reading disorders

Despite phonics being currently used as the preferred teaching method, reading disorders such as developmental dyslexia are still prevalent world-wide. Moreover, it has been noted that while showing similar phonological deficits in different countries, children with dyslexia exhibit different manifestations of the condition, depending on the orthographic transparency of the language being learned. In languages with transparent orthographies, reading disabilities become apparent with extremely slow and effortful phonological recoding, coupled by poor spelling.

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[24] This survey, first conducted in 2001, and subsequently every 5 years, compares the reading attainment and attitudes to reading of 9 and 10 year old children in 41 countries. The PIRLS reading achievement scale was established to have a mean of 500 and a standard deviation of 100.

In languages with opaque orthographies it is mainly poor accuracy that helps diagnosis, in addition to slow reading and poor spelling (Ziegler & Goswami, 2005). An interesting study by Hanley et al (2004) followed up the results of a previous study showing that Welsh-speaking children aged between 5 and 7 years outperformed their English-speaking counterparts at reading words and non-words (Spencer & Hanley, 2003). The follow-up study showed that at age 11, both groups had attained comparable word and non-word reading skills. However, among poor readers, group differences remained as observed in the earlier study, whereby the poorest 25% of English readers continued to perform significantly worse on word and non-word accuracy than the lowest performing 25% of Welsh readers, who showed high accuracy level, albeit considerably slow reading. Therefore in the long term, the orthographic opacity of English was shown to be detrimental to poor readers, relative to the transparency of Welsh.

What might be done in order to bridge the gaps between learners of opaque and transparent orthographies, and help poor readers catch up with their peers? Some have gone as far as calling for a spelling reform, in favour of a more transparent writing system (e.g. Abercrombie & Daniels, 2006). Such a drastic step is not unheard of. For example, in 1928, the government of the newly founded Republic of Turkey changed the Turkish writing system from Arabic script to Roman script. Similarly, in the 1950’s and 60’s, the Chinese government promoted the development of Pinyin; the simplified phonetic form of Chinese, officially implemented in 1979, and primarily used for early reading instruction (Neijt, 2006). Minor changes to English spelling have also been seen throughout history, mainly in the form of regional variants to words such as *programme / program*, *centre / center*, and *humour / humor*, as well as the recent phenomenon of “keyboard phonetic shorthand” such as *C U @ 4* (see you at four) and *I’ll B L8* (I’ll be late). However, officially ‘phoneticising’ the English writing system carries concerns that such a reform would lead to the elimination of the etymological origin of the language and may render original literature inaccessible. Consider a famous passage, which often emerges in websites and other scriptures relating to English spelling reforms:

A Plan for the improvement of English Spelling, by “Mark Twain”[25]:

“*For example, in Year 1 that useless letter "c" would be dropped to be replased either by "k" or "s," and likewise "x" would no longer be part of the alphabet. The only kase in which "c" would be retained would be the "ch" formation, which will be dealt with later. Year 2 might reform "w" spelling, so that "which" and "one" would take the same konsonant, wile Year 3 might well abolish "y" replasing it with "i" and Iear 4 might fiks the "g / j" anomali wonse and for all. Jenerally, then, the improvement would kontinue iear bai iear with Iear 5 doing awai with useless double konsonants, and Iears 6-12 or so modifaiing vowlz and the rimeining voist and unvoist konsonants. Bai Iear 15 or sou, it wud fainali bi posibl tu meik ius ov thi ridandant letez "c," "y," and "x" - bai now jast a memori in the maindz ov ould doderez - tu riplais "ch," "sh," and "th" rispektivli. Fainali, xen, aafte sam 20 iers ov*

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[25] Although this passage has been attributed to Mark Twain, the true origin is questionable, as no such quote has been found in any of Twain’s works. In his book “Another Almanac of Words at Play”, author Willard R. Epsy (1980; pp. 79-80) notes that this passage was in fact written by a person called M.J. Shields, in a letter to the *Economist*.

orxogrefkl riform, wi wud hev a lojikl, kohirnt speling in ius xrewawt xe Ingliy-spiking werld".

As a native Hebrew speaker, likely to resort to an exaggerated use of phonological assembly while reading English, I found this form of writing extremely difficult to read, and can therefore imagine that for a skilled native English reader this might be far from a logical or coherent piece of writing. Indeed, a spelling reform in favour of a more transparent English orthography might be more detrimental than beneficial, and so a focus on remedial intervention for reading difficulties may be more appropriate. An important aspect of these interventions must take into consideration not only the psycholinguistic component of reading but also the affective component. It is plausible that the "give-up" threshold of children with reading difficulties, learning to read an opaque orthography may be higher than that of children encountering difficulty in learning to read a transparent orthography (e.g. Paulesu, 2006). Therefore, development of teaching strategies must also focus on encouragement and motivation. In this respect, early learners of Hebrew may have an advantage over learners of English, since the vowelised form of Hebrew is entirely transparent, such that beginner readers learn initially by phonological assembly.

The differences in reading attainment between different languages in regular readers and differential manifestations of reading disability may bear particular importance for bilingual and multilingual children at risk of developing reading disorders. A prevalent problem in the education system faced with bilingual children is that attenuation of reading acquisition in L2 or L3 is often attributed to lower language proficiency (Cline & Frederickson, 1999; Geva, 2006; Uno, Wydell, Kato, Itoh & Yoshino, 2008). This assumption may mask an underlying deficit which could be overlooked. For example, Uno and colleagues (2008) presented the case of EM, a girl born in UK to Japanese parents. Her first language was Japanese, which was spoken at home, and her second language was English, which she began to learn at age four, upon entry to nursery school. With time, English became her dominant language, though Japanese was spoken at home, in Saturday school and during annual family visits to Japan. At the age of 8/9 it became apparent that EM was having difficulties with reading and writing in both languages. Suspecting dyslexia, her parents sought advice from the school counsellor, who maintained that her problems stemmed from bilingualism and suggested that EM be encouraged to use English at home. Unable to provide an English-speaking environment at home, EM's parents sent her to a private boarding school at the age of 11, where problems in both languages persisted, despite extra-curricular tuition of English for speakers of other languages (ESOL). At 14, EM's parents insisted that she be assessed professionally, and indeed, upon assessment in both English and Japanese, it was concluded that EM's language difficulties were not due to dyslexia, but to specific language impairment (SLI)[26].

Another interesting example was the case of AS (Wydell & Butterworth, 1999), a Japanese-English bilingual whose phonological dyslexia was detected *thanks* to his bilingualism. AS was born in Japan to highly literate native English speaking

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[26] Though some argue that SLI is a severe form of developmental dyslexia (see Bishop & Snowling, 2004 for a comprehensive review)

parents, and showed normal reading acquisition and attainment in Japanese, but impaired reading in English. At age 13, AS was diagnosed with dyslexia and commenced intensive tuition of English reading and writing by a speech therapist. Despite his phonological deficit, AS was subsequently able to complete an academic degree in an English-speaking country thanks to relatively early intervention (Wydell & Kondo, 2003). Since AS displayed no signs of reading disability in Japanese, had he not been a fluent bilingual, there would have been little reason to suspect that his problems with reading in English were not simply related to inferior proficiency and his phonological deficit might have gone undetected for a long time.

These two cases, reported in the UK, bring to mind concerns about several potential similar cases in other regions of the world where bilingualism is prevalent. Although the impairments of EM and AS were eventually diagnosed, several other children may not benefit from access to language-specialists and adequately trained educators. On the other hand, some bilingual or multilingual children (and adults) display attenuation in reading acquisition of L2 or L3, which may not necessarily stem from a reading disorder, but may in fact be related to the complexity of the writing system, as seen in the considerably slow Hebrew reading by native Spanish trilinguals in the present study. Moreover, in some cases knowledge of an additional language may be the source of poor reading performance. Such observations are generally attributed to cross-language transfer of skills (Cummins, 1979; Durgunoglu & Hancin, 1992; Wang et al, 2003). In these instances, multilingual individuals may be at risk of being wrongly or “over”-

diagnosed with reading disorders (Geva, 2006). The present study showed that even in opaque orthographies such as Hebrew, the cognitive system ‘prefers’ to rely on phonological processing whenever possible. Moreover, native Hebrew readers showed an exaggerated reliance on phonological processing, while reading in their second and third languages, as compensation for the inability to successfully use this strategy in their native language. Therefore, an observation which could be initially attributed to inferior language proficiency was shown to be related to a qualitatively different processing mechanism, influenced by the absence of phonemic information in the native language.

A greater understanding of bilingual language processing and the influence that the native language may have on the processing of the second language, beyond a simple cross-language transfer of strategy is therefore paramount. Moreover, attention must be given to developing strategies which capitalise on the strengths of multilingualism in aiding struggling readers to achieve normative literacy skills in their different languages.

6.7.3 Acquired reading disorders

As outlined in Chapter 2, another gamut of reading disorders is related to aphasia, caused by neurological damage in patients who had normal literacy skills prior to their lesion(s). Although each aphasic patient presents with a unique pathological profile, the manifestation of symptoms can be grouped and classified under a few common categories, e.g. transcortical motor aphasia, transcortical sensory aphasia, conduction aphasia etc. (Dronkers, 1996; Gazzaniga, Ivry & Mangun, 1998; Price, 2000). Similarly, acquired dyslexia can be classified into “phonological”, “surface” or “deep”, according to the type of impairment associated with the damage (Marshall & Newcombe, 1973; see Chapter 2, section 2.3, To read and read not…). Neurological patients tend to show some degree of recovery due to neural plasticity, which enables the spared neural components to compensate for the lost function (Hinshelwood, 1902; Newcombe, Marshall, Carrivick & Hiorns; Paradis, 1977). Therapeutic intervention strategies are therefore typically directed at strengthening the preserved functions to encourage or accelerate recovery (reviewed by Springer, 2008). For example, impairments associated with acquired phonological dyslexia can be ameliorated by re-training grapheme-to-phoneme conversion. At the initial stages of re-training, single letters are matched to phonemes. This is followed by generation of words for each letter and segmenting out initial phonemes for each word. Once letter-sound correspondences are mastered, more complex grain units are gradually introduced until patients are able to phonologically assemble words. This type of intervention was shown to help a stroke patient with a left fronto-temporal lesion to divert resources to the spared lingual gyrus and achieve successful reading of regular non-words (Small, Flores & Noll, 1998).

For acquired surface dyslexia, where the ability to phonologically assemble words is typically preserved, intervention is targeted specifically at improving visual word recognition. This can be efficiently accomplished via the use of mnemonic techniques, i.e. pairing orthographic word forms with matched objects or pictures and associating semantic, as well as phonological cues to written words (e.g. Byng & Coltheart, 1986; Weekes & Coltheart, 1996).

Treatment for deep dyslexia requires a combination of grapheme-to-phoneme conversion training and re-establishing contextual criteria for pronunciation (de Partz, 1986; Mitchum & Berndt, 1991). Once grapheme-to-phoneme conversion rules are mastered, regularisation errors can be minimised using mnemonic techniques, followed by exercises of written reproduction and / or selective reminding (e.g. Berninger, Lester, Sohlberg & Mateer, 1991). The former is designed to strengthen the associations between words and their orthographic forms, while the latter serves to draw attention to and facilitate retrieval of spoken word codes from long-term memory, thus strengthening the association between orthographic forms and phonological codes.

The examples described above were taken from reported cases of successful rehabilitation, with the exception of that reported by Mitchum and Berndt (1991). The patient studied by these authors was diagnosed with deep dyslexia following a stroke, which resulted in a large infarction in the left hemisphere encompassing frontal, temporal and parietal cortex. The patient was able to re-learn letter-to-sound associations of simple regular graphemes, but was not able to learn the association between more ambiguous letter clusters, which are prevalent in English, and their phonology. Moreover, the patient was unable to grasp the contextual relationship between phonemes and words. The authors attributed this to a severe deficit in phonological short-term memory, and thus concluded that re-establishing grapheme-to-phoneme conversion would have little impact on functional reading unless the phonological short-term memory deficit could be improved as well.

Efficient intervention requires a detailed assessment of the lost and the preserved functions, in order to ascertain whether the relatively spared components can be exploited to aid recovery, and whether a particular method is likely to benefit a patient exhibiting a particular impairment. The advent of non-invasive functional neuroimaging techniques in recent years has made this possible by enabling not only the association between behavioural manifestations of impairments and their underlying neural substrates, but also the visualisation of the functional role of specific regions in the lesioned brain. In this respect, much insight can be gained about remedial intervention to aid recovery by observing the neural architecture of language representation in normally functioning brains. For example, the present study revealed that the right fusiform gyrus was sensitive to word frequency and lexicality as well as to orthographic transparency. Increasing current knowledge about the role of this region in reading, which has not been thoroughly investigated so far, may help devise therapeutic strategies focussed on re-establishing orthographic processing in the left visual field. Similarly, observing that the right superior temporal gyrus may be involved specifically in second language processing could provide guidance towards devising methods geared at accelerating the recovery of non-native languages, in cases of language-selective impairments in multilingual patients.

6.8 Concluding thoughts

As most research projects, the present findings constitute just the tip of the iceberg in the quest for understanding the remarkable versatility of the human brain. So long as curiosity and hunger for knowledge prevail, the light of language, the art of reading and the phenomenon of multilingualism continue to fuel new ingenious ways of answering questions and generating new ones.

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Appendix 1
Participant questionnaire

Name				M/F
Age	Education	(place and years)	Test	
Country of birth		(years)	Present country	(years)
Other countries				
Languages				(AoA)
Best language for:	Speaking			(Preferred language)
	Reading			
	Writing			
Language (s) spoken at home				
In which language do you			read	write
		literature		
		newspapers		
		correspondence		
		professional		
		other		
listen to music		Estimate how many hours a week are you exposed to:		
watch TV		English		
listen to radio		Spanish		
other		Hebrew		
What language do you think in (internal monologue)				
Which language do you count in?				
Which language would you use in a strongly emotional situation?				
Do you confuse words between languages?				
Which to which?				
Comments:				

Appendix 2
Word and non-word stimuli used in experiments 1, 2, 4 and 5

Spanish									
High-frequency words				**Low-frequency words**				**Non-words**	
Short		**Long**		**Short**		**Long**		**Short**	**Long**
Agua	(water)	Ámbito	(field)	Abad	(priest)	Acanto	(acanthus)	Afur	Ableta
Aire	(air)	Bosque	(forest)	Bazo	(spleen)	Bípedo	(biped)	Bapi	Bafege
Baño	(bath)	Cadena	(chain)	Búho	(owl)	Boñiga	(cowpat)	Bedó	Bullán
Boca	(mouth)	Diario	(diary)	Cuña	(wedge)	Dehesa	(meadow)	Dipu	Dopite
Café	(coffee)	Dinero	(money)	Domo	(dome)	Fogata	(bonfire)	Fipa	Gépilo
Cine	(cinema)	Envase	(package)	Faro	(lighthouse)	Genoma	(genome)	Jori	Lertio
Dama	(lady)	Figura	(figure)	Fosa	(grave)	Hocico	(muzzle)	Letí	méchin
Flan	(custard)	Jardín	(garden)	Hada	(fairy)	Lápida	(memorial stone)	Mase	Nerjón
Gato	(cat)	Lluvia	(rain)	Iodo	(iodine)	Marjal	(moor)	Mipu	Ñarpil
Hoja	(leaf)	Música	(music)	Maña	(skill)	Mármol	(marble)	Ocol	obchol
Mano	(hand)	Novela	(novel)	Obús	(shell)	Pábulo	(nourishment)	Pebo	Patira
Papá	(father)	Página	(page)	Puya	(rod)	Pelaje	(fur)	Pité	Peteno
Puré	(mash)	Piedra	(stone)	Rabo	(tail)	Rebujo	(muffler)	Rugá	Retefa
Sala	(hall)	Tetera	(kettle)	Tino	(sense)	Secuaz	(friend)	Sire	Selual
Taza	(mug)	Zapato	(shoe)	Zuro	(no translation)	Turrón	(nougat)	Tuja	Vetino

English					
High-frequency words		Low-frequency words		Non-words	
Short	Long	Short	Long	Short	Long
Art	Apple	Ace	Acorn	Bam	Brank
Bar	Digit	Bay	Beard	Bez	Cetin
Bed	Frame	Bud	Broom	Cag	Cland
Cab	Grass	Cub	Calyx	Deg	Dalft
Car	Lemon	Den	Crust	Fud	Durrp
Dog	Match	Fox	Brash	Gop	Elter
Egg	Mouse	Gig	Gauge	Ige	Grink
Hat	Office	Gut	Ladle	Lud	Lorge
Job	Peace	Hob	Marsh	Mel	Motch
Man	Pitch	Lac	Niece	Nak	Nirth
Nut	Plant	Mod	Pavid	Oad	Palth
Pen	River	Pea	Peach	Ped	Rople
Sea	Salad	Ray	Spoon	Sab	Shart
Sun	Table	Spa	Thorn	Som	Talsh
Tax	Thing	Toy	Voice	Tob	Vogre

Hebrew															
High-frequency words						**Low-frequency words**						**Non-words**			
Short			**Long**			**Short**			**Long**			**Short**		**Long**	
ארץ	*eretz*	*(country)*	אבטחה	*avtaxa*	(security)	אצה	*atza*	(seaweed)	אטליז	*itliz*	(butcher)	בגש	*bagash*	בגושה	*bagusha*
בית	*bait*	(house)	בדיחה	*bdixa*	(joke)	ברך	*berex*	(knee)	אפרוח	*efroax*	(chick)	גמץ	gamatz	אגלחה	*aglaxa*
בלש	*balash*	(detective)	בקבוק	*bakbook*	(bottle)	גמד	*gamad*	(dwarf)	בבואה	*babu’a*	(reflection)	דגא	*daga*	בעקול	*ba’akol*
גדה	*gada*	(bank)	דוגמא	*doogma*	(example)	דוב	*dov*	(bear)	דגלון	*diglon*	(flag)	וגק	*vagak*	דשיחי	*deshixi*
דגש	*dagesh*	(accent)	חוברת	*xoveret*	(magazine)	דלי	*dli*	(bucket)	דלפון	*dalfon*	(tramp)	דשס	*dashas*	זהיכה	*zehixa*
ותק	*vetek*	(seniority)	חשבון	*xeshbon*	(bill)	זאב	*zeev*	(wolf)	טוזיג	*toozig*	(picnic)	חבף	*xabaf*	חשצון	*xeshtzon*
זהב	*zahav*	(gold)	כותרת	*koteret*	(title)	חרב	*xerev*	(sword)	מרווה	*marva*	(sage)	כאר	*ka’ar*	יעינט	*ye’int*
חול	*xol*	(sand)	כרטיס	*kartis*	(ticket)	טחב	*taxav*	(damp)	משקוף	*mashkof*	(doorframe)	לנר	*lanar*	לגוסה	*legosa*
כנף	*kanaf*	(wing)	ממשלה	*memshala*	(government)	לסת	*leset*	(jaw)	נסיוב	*nasiob*	(serum)	ניץ	*nitz*	מגפוד	*magfo*
מדע	*mada*	(science)	מדפסת	*madpeset*	(printer)	משי	*meshi*	(silk)	עווית	*avit*	(spasm)	סשל	*seshel*	נשצוי	*nashtzoi*
נחל	*naxal*	(river)	משאית	*masait*	(truck)	מצה	*matza*	(matzoh)	עששית	*ashashit*	(oil-lamp)	עזג	*azag*	פולחי	*polxi*
נפט	*neft*	(oil)	פקודה	*pkuda*	(command)	סדן	*sadan*	(anvil)	פגיון	*pigion*	(dagger)	פלם	*pelem*	פעיבה	*pe’iva*
פרי	*pri*	(fruit)	רמזור	*ramzor*	(trafficlight)	עלם	*elem*	(lad)	פסנתר	*psanter*	(piano)	רנל	*renel*	רטלוש	*ratlosh*
פרח	*perax*	(flower)	תפריט	*tafrit*	(menu)	פאה	*pe’a*	(wig)	שלגון	*shalgon*	(ice-lolly)	שסד	*shasad*	שדיסן	*shdisan*
פתק	*petek*	(note)	תקציב	*taktziv*	(budget)	פחם	*pexam*	(coal)	שמרטף	*shmartaf*	(babysitter)	תדב	*tadev*	תפומה	*tfuma*

Appendix 3
Statistical values of regression analysis for demographic factors of Experiment 1 (bilingual standard naming)

a. Effect of gender on overall naming latency

Condition	R^2	df	F	beta	t	P
L1 naming latency	0.026	1,89	2.39	-0.16	-1.55	0.13
English naming latency	0	1,59	0.14	-0.02	-0.12	0.91

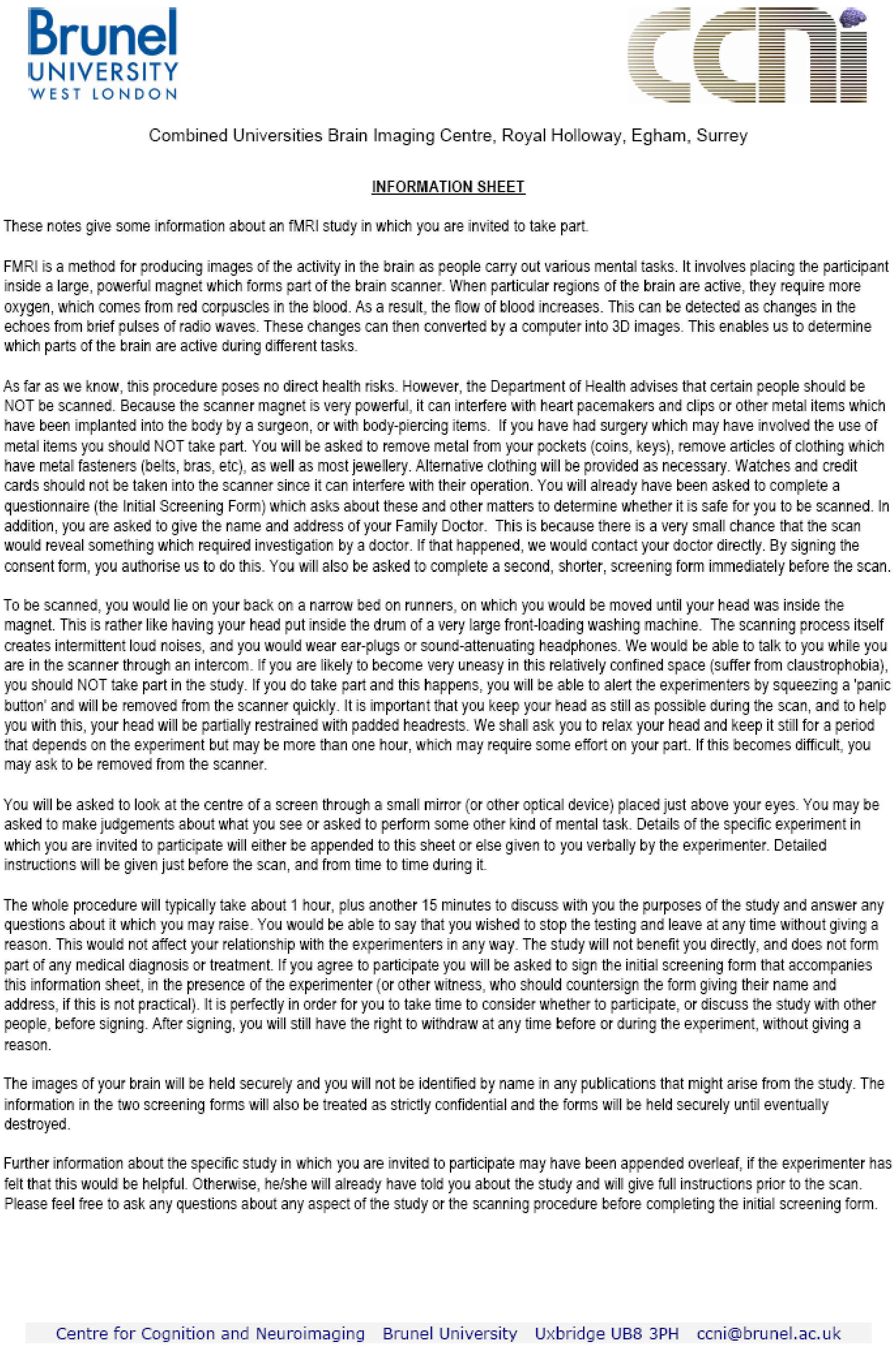
b. Effect of age on overall naming latency

Condition	R^2	df	F	beta	t	P
L1 naming latency	0.01	1,89	0.14	0.12	0.12	0.91
English naming latency	0.01	1,59	0.39	0.08	0.63	0.53

c. Effect of formal education on overall naming latency

Condition	R^2	df	F	beta	t	P
L1 naming latency	0.01	1,89	1.09	-0.11	-1.05	0.29
English naming latency	0.001	1,59	0.05	0.03	9.77	0.83

Appendix 4
Functional MRI Information Sheet



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INFORMATION SHEET

These notes give some information about an fMRI study in which you are invited to take part.

FMRI is a method for producing images of the activity in the brain as people carry out various mental tasks. It involves placing the participant inside a large, powerful magnet which forms part of the brain scanner. When particular regions of the brain are active, they require more oxygen, which comes from red corpuscles in the blood. As a result, the flow of blood increases. This can be detected as changes in the echoes from brief pulses of radio waves. These changes can then converted by a computer into 3D images. This enables us to determine which parts of the brain are active during different tasks.

As far as we know, this procedure poses no direct health risks. However, the Department of Health advises that certain people should be NOT be scanned. Because the scanner magnet is very powerful, it can interfere with heart pacemakers and clips or other metal items which have been implanted into the body by a surgeon, or with body-piercing items. If you have had surgery which may have involved the use of metal items you should NOT take part. You will be asked to remove metal from your pockets (coins, keys), remove articles of clothing which have metal fasteners (belts, bras, etc), as well as most jewellery. Alternative clothing will be provided as necessary. Watches and credit cards should not be taken into the scanner since it can interfere with their operation. You will already have been asked to complete a questionnaire (the Initial Screening Form) which asks about these and other matters to determine whether it is safe for you to be scanned. In addition, you are asked to give the name and address of your Family Doctor. This is because there is a very small chance that the scan would reveal something which required investigation by a doctor. If that happened, we would contact your doctor directly. By signing the consent form, you authorise us to do this. You will also be asked to complete a second, shorter, screening form immediately before the scan.

To be scanned, you would lie on your back on a narrow bed on runners, on which you would be moved until your head was inside the magnet. This is rather like having your head put inside the drum of a very large front-loading washing machine. The scanning process itself creates intermittent loud noises, and you would wear ear-plugs or sound-attenuating headphones. We would be able to talk to you while you are in the scanner through an intercom. If you are likely to become very uneasy in this relatively confined space (suffer from claustrophobia), you should NOT take part in the study. If you do take part and this happens, you will be able to alert the experimenters by squeezing a 'panic button' and will be removed from the scanner quickly. It is important that you keep your head as still as possible during the scan, and to help you with this, your head will be partially restrained with padded headrests. We shall ask you to relax your head and keep it still for a period that depends on the experiment but may be more than one hour, which may require some effort on your part. If this becomes difficult, you may ask to be removed from the scanner.

You will be asked to look at the centre of a screen through a small mirror (or other optical device) placed just above your eyes. You may be asked to make judgements about what you see or asked to perform some other kind of mental task. Details of the specific experiment in which you are invited to participate will either be appended to this sheet or else given to you verbally by the experimenter. Detailed instructions will be given just before the scan, and from time to time during it.

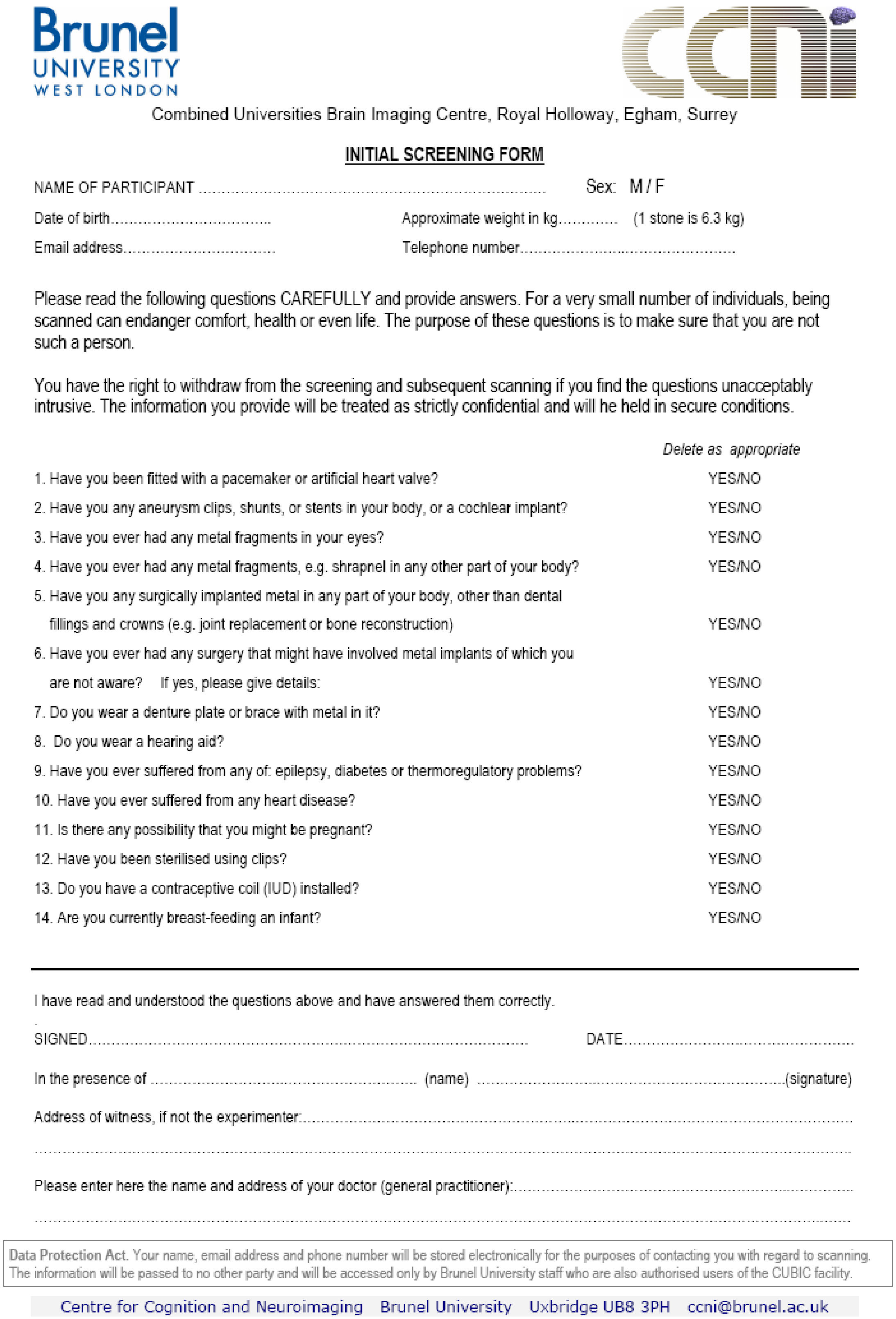
The whole procedure will typically take about 1 hour, plus another 15 minutes to discuss with you the purposes of the study and answer any questions about it which you may raise. You would be able to say that you wished to stop the testing and leave at any time without giving a reason. This would not affect your relationship with the experimenters in any way. The study will not benefit you directly, and does not form part of any medical diagnosis or treatment. If you agree to participate you will be asked to sign the initial screening form that accompanies this information sheet, in the presence of the experimenter (or other witness, who should countersign the form giving their name and address, if this is not practical). It is perfectly in order for you to take time to consider whether to participate, or discuss the study with other people, before signing. After signing, you will still have the right to withdraw at any time before or during the experiment, without giving a reason.

The images of your brain will be held securely and you will not be identified by name in any publications that might arise from the study. The information in the two screening forms will also be treated as strictly confidential and the forms will be held securely until eventually destroyed.

Further information about the specific study in which you are invited to participate may have been appended overleaf, if the experimenter has felt that this would be helpful. Otherwise, he/she will already have told you about the study and will give full instructions prior to the scan. Please feel free to ask any questions about any aspect of the study or the scanning procedure before completing the initial screening form.

Centre for Cognition and Neuroimaging Brunel University Uxbridge UB8 3PH ccni@brunel.ac.uk

Appendix 5
Initial Screening Form



Brunel
UNIVERSITY
WEST LONDON

ccni

Combined Universities Brain Imaging Centre, Royal Holloway, Egham, Surrey

INITIAL SCREENING FORM

NAME OF PARTICIPANT ………………………………………………………………… Sex: M / F

Date of birth…………………………….. Approximate weight in kg………… (1 stone is 6.3 kg)

Email address…………………………… Telephone number………………………………………

Please read the following questions CAREFULLY and provide answers. For a very small number of individuals, being scanned can endanger comfort, health or even life. The purpose of these questions is to make sure that you are not such a person.

You have the right to withdraw from the screening and subsequent scanning if you find the questions unacceptably intrusive. The information you provide will be treated as strictly confidential and will he held in secure conditions.

	Delete as appropriate
1. Have you been fitted with a pacemaker or artificial heart valve?	YES/NO
2. Have you any aneurysm clips, shunts, or stents in your body, or a cochlear implant?	YES/NO
3. Have you ever had any metal fragments in your eyes?	YES/NO
4. Have you ever had any metal fragments, e.g. shrapnel in any other part of your body?	YES/NO
5. Have you any surgically implanted metal in any part of your body, other than dental fillings and crowns (e.g. joint replacement or bone reconstruction)	YES/NO
6. Have you ever had any surgery that might have involved metal implants of which you are not aware? If yes, please give details:	YES/NO
7. Do you wear a denture plate or brace with metal in it?	YES/NO
8. Do you wear a hearing aid?	YES/NO
9. Have you ever suffered from any of: epilepsy, diabetes or thermoregulatory problems?	YES/NO
10. Have you ever suffered from any heart disease?	YES/NO
11. Is there any possibility that you might be pregnant?	YES/NO
12. Have you been sterilised using clips?	YES/NO
13. Do you have a contraceptive coil (IUD) installed?	YES/NO
14. Are you currently breast-feeding an infant?	YES/NO

I have read and understood the questions above and have answered them correctly.

SIGNED………………………………………………………………………………… DATE…………………………………………

In the presence of ……………………………………………… (name) ………………………………………………………(signature)

Address of witness, if not the experimenter:……………………………………………………………………………………………

……

Please enter here the name and address of your doctor (general practitioner):…………………………………………………………

……

Data Protection Act. Your name, email address and phone number will be stored electronically for the purposes of contacting you with regard to scanning. The information will be passed to no other party and will be accessed only by Brunel University staff who are also authorised users of the CUBIC facility.

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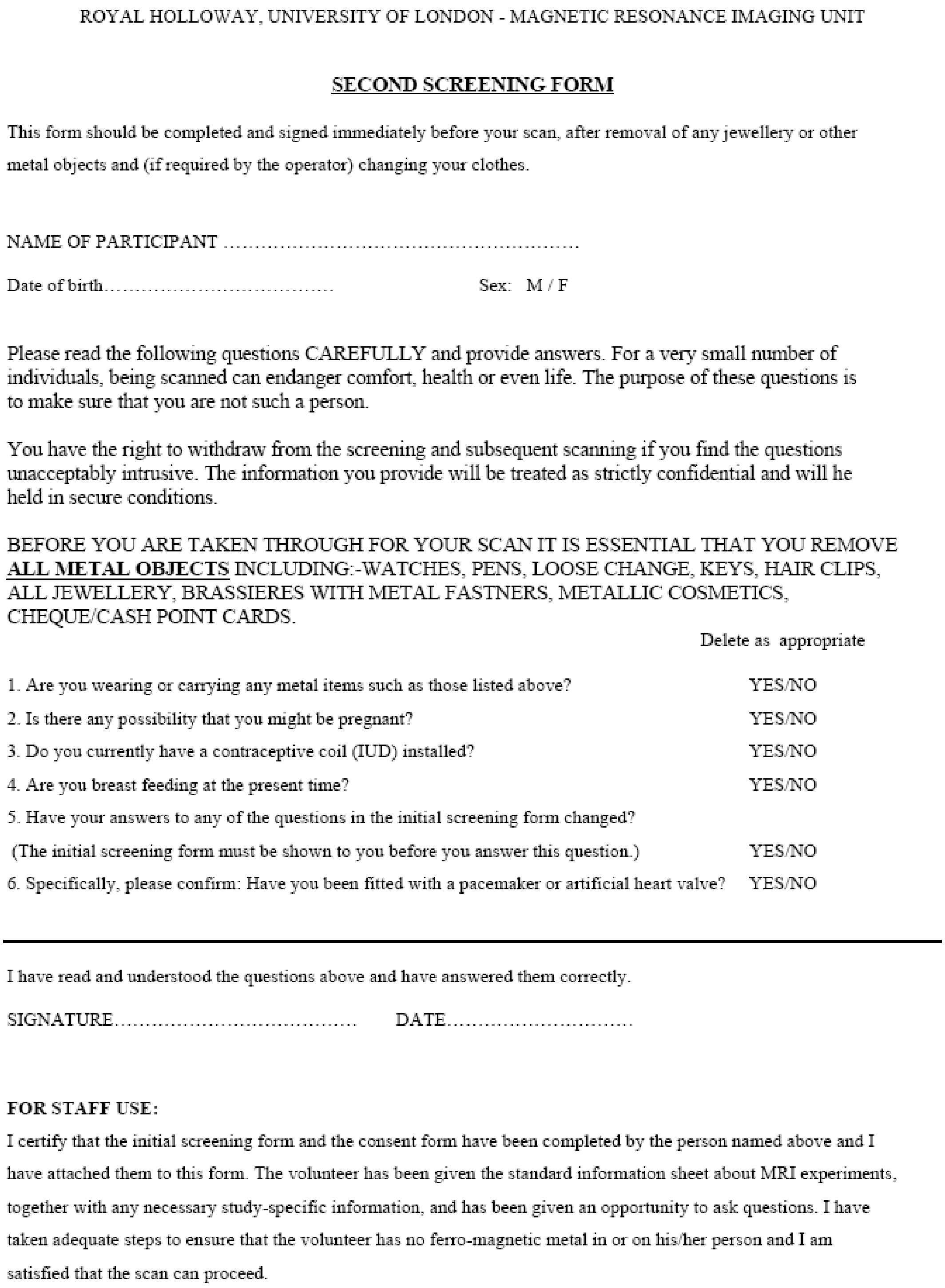
Appendix 6
Secondary Screening Form



ROYAL HOLLOWAY, UNIVERSITY OF LONDON - MAGNETIC RESONANCE IMAGING UNIT

<u>SECOND SCREENING FORM</u>

This form should be completed and signed immediately before your scan, after removal of any jewellery or other metal objects and (if required by the operator) changing your clothes.

NAME OF PARTICIPANT ………………………………………………….

Date of birth……………………………… Sex: M / F

Please read the following questions CAREFULLY and provide answers. For a very small number of individuals, being scanned can endanger comfort, health or even life. The purpose of these questions is to make sure that you are not such a person.

You have the right to withdraw from the screening and subsequent scanning if you find the questions unacceptably intrusive. The information you provide will be treated as strictly confidential and will he held in secure conditions.

BEFORE YOU ARE TAKEN THROUGH FOR YOUR SCAN IT IS ESSENTIAL THAT YOU REMOVE **<u>ALL METAL OBJECTS</u>** INCLUDING:-WATCHES, PENS, LOOSE CHANGE, KEYS, HAIR CLIPS, ALL JEWELLERY, BRASSIERES WITH METAL FASTNERS, METALLIC COSMETICS, CHEQUE/CASH POINT CARDS.

Delete as appropriate

1. Are you wearing or carrying any metal items such as those listed above? YES/NO
2. Is there any possibility that you might be pregnant? YES/NO
3. Do you currently have a contraceptive coil (IUD) installed? YES/NO
4. Are you breast feeding at the present time? YES/NO
5. Have your answers to any of the questions in the initial screening form changed?
(The initial screening form must be shown to you before you answer this question.) YES/NO
6. Specifically, please confirm: Have you been fitted with a pacemaker or artificial heart valve? YES/NO

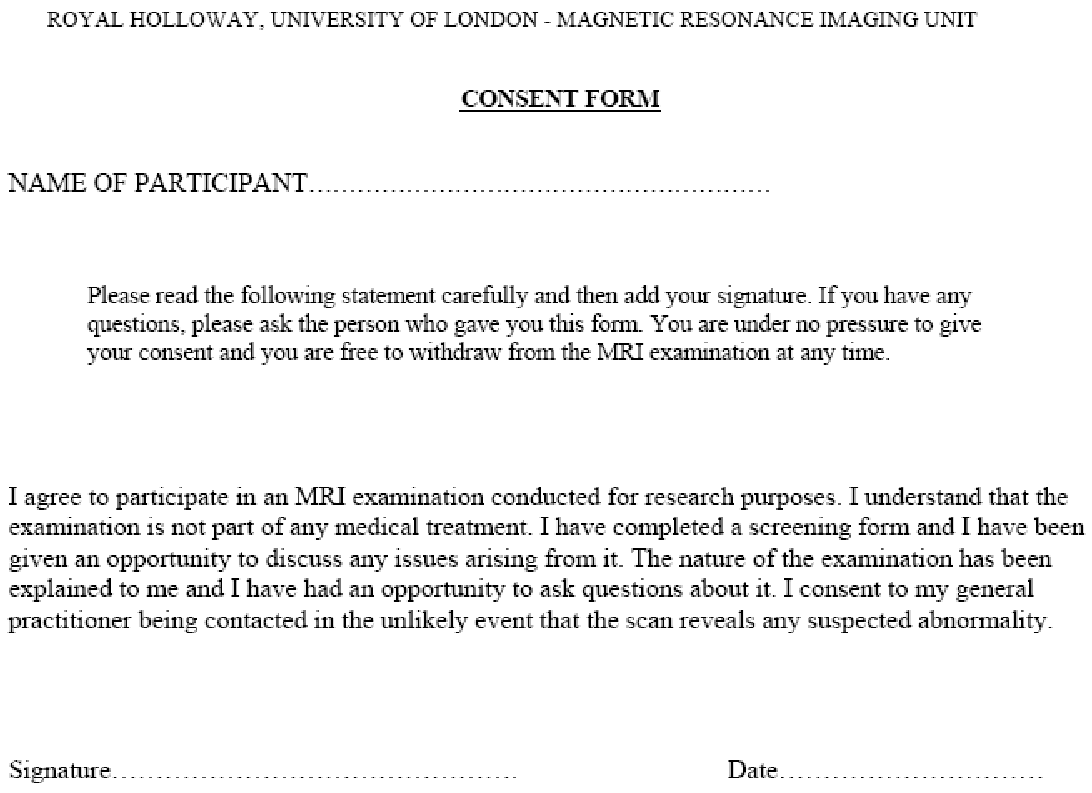
I have read and understood the questions above and have answered them correctly.

SIGNATURE………………………………… DATE…………………………

FOR STAFF USE:

I certify that the initial screening form and the consent form have been completed by the person named above and I have attached them to this form. The volunteer has been given the standard information sheet about MRI experiments, together with any necessary study-specific information, and has been given an opportunity to ask questions. I have taken adequate steps to ensure that the volunteer has no ferro-magnetic metal in or on his/her person and I am satisfied that the scan can proceed.

Appendix 7
Consent Form



ROYAL HOLLOWAY, UNIVERSITY OF LONDON - MAGNETIC RESONANCE IMAGING UNIT

CONSENT FORM

NAME OF PARTICIPANT……………………………………………………

Please read the following statement carefully and then add your signature. If you have any questions, please ask the person who gave you this form. You are under no pressure to give your consent and you are free to withdraw from the MRI examination at any time.

I agree to participate in an MRI examination conducted for research purposes. I understand that the examination is not part of any medical treatment. I have completed a screening form and I have been given an opportunity to discuss any issues arising from it. The nature of the examination has been explained to me and I have had an opportunity to ask questions about it. I consent to my general practitioner being contacted in the unlikely event that the scan reveals any suspected abnormality.

Signature………………………………………… Date……………………………

Appendix 8
Words used in Experiment 3 (fMRI pilot)

Spanish				**English**		**Hebrew**					
High		**Low**		**High**	**Low**	**High**			**Low**		
Casa	(house)	Abad	(priest)	King	Mire	קסדה	*kasda*	(helmet)	זווית	*zavit*	(angle)
Calle	(street)	Fosa	(grave)	Debt	Sage	אורז	*orez*	(rice)	פיסח	*piseax*	(limp)
Meta	(goal)	Prez	(honour)	Myth	Mole	כביש	*kvish*	(road)	שסעת	*shasaat*	(schizophrenia)
Caja	(box)	Alelí	(gillyflower)	Bond	Wilt	בסיס	*basis*	(base)	כסיה	*ksia*	(glove)
Raza	(race)	Flan	(custard)	Robe	Hive	בובה	*booba*	(doll)	דרדק	*dardak*	(infant)
Llama	(flame)	Feto	(fetus)	Rock	Coil	משכן	*mishkan*	(residence)	רוטב	*rotev*	(sauce)
Baño	(bath)	Obús	(shell)	Scar	Curb	גבול	*gvul*	(border)	עמלה	*amla*	(commission)
Puré	(mash)	Ñapa	(no translation)	Food	Limb	מידע	*meida*	(information)	שריר	*shrir*	(muscle)
Olor	(smell)	Faro	(lighthouse)	Deal	Chess	קרחת	*karaxat*	(baldness)	טופז	*topaz*	(topaz)
Acto	(act)	Mirra	(resin)	Suit	Dove	משרד	*misrad*	(office)	אוכף	*ookaf*	(saddle)
Vaso	(glass)	Cayo	(islet)	Film	Heap	אביב	*aviv*	(spring)	נחושת	*nexoshet*	(copper)
Tela	(fabric)	Búho	(owl)	List	Arid	מטרה	*matara*	(goal)	טיעה	*ti'a*	(plantation)
Agua	(water)	Ojal	(buttonhole)	Boot	Welt	כדור	*kadur*	(ball)	תצרף	*tatzref*	(puzzle)
Lomo	(beef)	Foro	(court)	Firm	Reef	ארגז	*argaz*	(box)	הדיוט	*hediot*	(layperson)
Cama	(bed)	Laca	(lacquer)	Sale	Onyx	תפוז	*tapuz*	(orange)	טוזיג	*toozig*	(picnic)
Trigo	(wheat)	Ñaco	(no translation)	Bank	Soup	מרכז	*merkaz*	(centre)	אבנט	*avnet*	(belt)
Trama	(plot)	Lama	(mud)	Wind	Echo	אזור	*ezor*	(area)	נסיוב	*nasiob*	(serum)
Borde	(border)	Jaca	(pony)	Shop	Mint	עתיד	*atid*	(future)	גנזך	*ginzax*	(archive)
Nariz	(nose)	Iodo	(iodine)	Team	Dole	מלצר	*meltzar*	(waiter)	צאצא	*tze'etza*	(offspring)
Onda	(wave)	Fósil	(fossil)	Slum	Brow	ארנק	*arnak*	(wallet)	אזמל	*izmel*	(chisel)

Appendix 9
Statistical values of regression analysis for demographic factors of Experiment 5 (trilingual standard naming)

i. Effect of gender on overall naming latency

Condition	R^2	$F_{(1,39)}$	beta	t	p
Spanish naming latency	0.002	0.09	0.05	0.29	0.77
Hebrew naming latency	0.02	0.85	0.15	0.92	0.36
English naming latency	0.001	0.03	-0.03	-0.19	0.85

ii. Effect of age on overall naming latency

Condition	R^2	$F_{(1,39)}$	beta	t	p
Spanish naming latency	0.005	0.19	0.07	0.44	0.67
Hebrew naming latency	***0.31***	***17.21***	***0.56***	***4.15***	***<0.001***
English naming latency	***0.14***	***5.98***	***0.37***	***2.44***	***0.02***

iii. Effect of formal education on overall naming latency

Condition	R^2	$F_{(1,39)}$	beta	t	p
Spanish naming latency	0.08	3.50	0.29	1.87	0.07
Hebrew naming latency	0.08	3.25	0.28	1.80	0.08
English naming latency	0.03	1.26	0.18	1.12	0.27