

A BEHAVIOURAL AND ELECTROPHYSIOLOGICAL  
INVESTIGATION OF CHINESE CHARACTER RECOGNITION  
AS REVEALED BY THE CHARACTER SUPERIORITY EFFECT

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## Abstract

A Behavioural and Electrophysiological Investigation of Chinese Character Recognition as Revealed by the Character Superiority Effect

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The word superiority effect is one of the most robust findings in English word recognition. It is commonly believed that the coarse-scale configurational information in a lexical context is more familiar to readers and therefore facilitates the identification of its component letters. Aiming at reassessing the character superiority effect in the Chinese language, this thesis first reports an empirical study determining the fundamental factor of stimulus presentation size by establishing the optimal retinal image size in normal Chinese reading. It then presents a series of experiments which examined if the Chinese character superiority can be obtained by using the stringent Reicher-Wheeler task and carefully manipulated stimulus conditions which featured impairment of spatial configuration information of characters to various degrees. The thesis further presents a study which investigated the character superiority effect in lateralized display and its neural correlates by comparing the event-related potentials (ERPs) to characters versus character-like stimuli. The findings show the character superiority over pseudocharacters and several types of character-like stimuli in central and lateralized display. More importantly, a temporal-spatial profile was established for Chinese character recognition.

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## **Chapter 1. General Introduction I: The Word Superiority Effect in English word recognition**

To investigate the Word Superiority Effect in Chinese, as the title of the thesis states, it is essential to introduce the general background of the research topic. As the first part of this General Introduction, this chapter will first define the Word Superiority Effect (WSE) and then explain how studying the WSE has contributed towards the understanding of letter and word recognition and particularly its theory construction. Various factors that have been found to affect the presence or the size of the WSE are also introduced, including word properties like length and frequency as well as visuo-perceptual factors such as the size and visual field of stimulus presentation. The chapter will also introduce the task to be employed to assess the WSE in Chinese and explain its advantage compared to other common tasks used in the area of word recognition.

### **1.1 What is the Word Superiority Effect?**

Research into visual word recognition using alphabetic languages, especially English, has seen substantial development since Cattell's early studies (Cattell, 1886). By severely limiting the amount of time for which a stimulus (e.g., letter, word, unrelated letter string) is presented, researchers have examined what physical characteristics of words are encoded by readers and over what time course this encoding takes place (for reviews see, e.g., Carr, 1986; Henderson, 1987; McClelland & Rumelhart, 1981). One of the most important findings from this kind of study is the context effects in visual word recognition. Following previous studies (e.g., McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982; Richman & Simon, 1989), the

context effects in visual word recognition refer to the phenomena that the nature of the context in which the visual contents of a word, letters in particular, has an impact on how these contents are perceived by readers, which are different from another line of research on how the sentential context in which words are embedded affects its processing. Among the well-established context effects in word recognition is the Word Superiority Effect (WSE). Specifically, when given the task of identifying which of two alternative letters (e.g., d or k) was contained in a briefly presented stimulus (known as the Reicher-Wheeler task), readers are more accurate when the letter occurred in a word (e.g., word, work) than in a pseudoword (pronounceable illegal letter string, e.g., wurd, wurd), in a nonword (unpronounceable illegal letter string, e.g., urwd, urwk), and occurred alone (e.g., ###d, ###k) (Carr, Lehmkuhle, Kottas, Astor-Stetson, & Arnold., 1976; Estes, 1975; Grainger, Bouttevin, Truc, Bastien, & Ziegler, 2003; Hildebrandt, Caplan, Sokol, & Torreano, 1995; Jordan & Bevan, 1994; McClelland & Rumelhart, 1981; Reicher, 1969; Wheeler, 1970). This advantage for words appears to be due to perceptual processing rather than to the use of some form of postperceptual guessing based on orthographic knowledge (e.g., Johnston, 1978). Consequently, in data-limited viewing conditions, individual letters presented in the context of words appear to be more perceptible than the same letters presented in pseudoword, nonword contexts or in isolation, and these context effects continue to exert considerable impact on theories of word and letter recognition. It should be pointed out that the WSE can also be shown in other tasks such as the lexical decision task. However, the Reicher-Wheeler is methodologically more suited to assessing the WSE compared to other commonly used tasks in the area of word recognition, which will be elaborated on below in Section 1.4.

## 1.2 The significance of the WSE to word recognition research

To understand the theoretical significance of the WSE in word recognition, it is important to address the notion of 'word recognition' and some of the characteristics of theory construction for word recognition. Firstly, word recognition theory construction can be divided into two stages according to the popularity of neurophysiologic techniques. Specifically, model building for word recognition started in the late 1960s (Morton's logogen model, 1969) and flourished during the following two decades until the mid 1990s with a variety of models (e.g., Carr & Pollatsek's parallel coding model, 1985; Coltheart & Rastle's dual route model, 1994; Jacobs & Grainger's semistochastic Interactive Activation Model, 1992; McClelland & Rumelhart's Interactive Activation Model, 1981; Paap, Newsome, McDanold, & Schvaneveldt's activation-verification model; Seidenberg & McClelland's distributed developmental model, 1989). Starting from the 1990s, with the neurophysiological techniques more widely adopted in psychology laboratories around the world, more and more researchers started to investigate the neuro-anatomical correlates of psychological effects in word recognition (e.g., Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999; McCarthy, Puce, Nobre, Bentin, & Allison, 1996) and to assess what influences findings from these neuro-anatomical studies impose on our knowledge of word recognition (e.g., Posner & Carr, 1992), though there have been several new models proposed (e.g., Whitney's SERIOL model, 2001; Davis's spatial coding model, 2010). One example of such influences is the transition of word recognition research from more macroscopic to more microscopic. Specifically, early models derived from pure psychophysical research typically characterise the process of word recognition in a general multi-layer hierarchical structure from visual input to orthography or phonology, e.g., input layer (letter features), hidden layer (letters), and output layer (word) in McClelland &

Rumelhart (1981)'s Interactive Activation Model. In contrast, a word recognition model in the context of neural coding would be more interested in describing the micro-structure of these layers. For example, Dehaene, Cohen, Sigman and Vinckier (2005) proposed a seven-layer hierarchy of local combination detectors which not only predicts that visual information is processed from as local contrast, oriented bars, letter fragments and eventually to as small words and recurring substrings, but also defines in what brain areas these seven processes are performed respectively. Other recent models include the Connectionist Dual Process model (e.g., Perry, Ziegler, & Zorzi, 2007) and the Bayesian Reader model (e.g., Norris, 2006).

Another characteristic of word recognition theory building is the two pairs of distinctions in defining the very term of 'word recognition'. As Posner and Carr (1992) remarked, if the notion of 'word recognition' was approached as questioning what exactly it is that a reader knows about a letter string the instant after lexical access has occurred which was not known the instant before and is necessary in performing a designated task, a word being recognized can be thought of as the activation of a set or list of linguistically relevant word properties including orthography, phonology, semantics and probably more (e.g., syntactic form class and associated argument structures). The first pair of distinction lies between the localized and the distributed views of word recognition. Specifically, this distinction concerns whether word recognition is accomplished in one single event of activating of a single node which stores the complete set of word properties or it comprises a series of such events at different times in a distributed network, each contributing to the activation of a single or a subset of word properties. Word recognition models in early days are typically localist

models<sup>1</sup> and have not been supported by neurophysiological evidence that multiple cortical areas rather than one single area in the brain are activated in response to a word stimulus. As pointed out in Posner and Carr (1992), if a computational model fails to incorporate this division of labor into separate localized processes, it will lose at least biological fidelity and probably computational adequacy as well. Indeed, different tasks place emphasis on different aspects of linguistic knowledge about a word, it is more likely that only some or a subset of the linguistic properties of a word are activated when it is viewed in a particular task and activation of a certain property can be stronger in one task than another. In a similar vein, existing models in word recognition are generally phenomenon-specific, each focusing on providing explanation or simulation for one or a few particular phenomena in word recognition such as the WSE, the word frequency effect, the orthographic neighbourhood effect. Table 1.1 summaries the major models up to date which have been specially designed for the WSE which can be grouped into five categories, namely, the interactive activation models, the serial verification model, the parallel coding model, the fuzzy logical model, and the dual-route processing models.

Despite the dissimilarities, these five categories of models share the common feature of constraining itself in a localized hierarchy from printed input to orthography or phonology. The reason why these localized models only describe an orthography or phonology output layer but not other output layer such as encoding semantics can be largely attributed to the fact that the WSE is typically obtained in the Reicher-Wheeler task, the lexical decision task, or less often in the naming task, which do not explicitly require semantic activation in order to respond correctly. Apart from taking a localized

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<sup>1</sup> According to Jacobs & Grainger (1994)'s review, the first distributed model of word recognition did not appear until 1986, though localist models still dominated after this time.

Family	Model	Task	Localized Distributed	One-way Interactive
Interactive activation	McClelland & Rumelhart (1981)	Reicher-Wheeler	Localized	Interactive
	Jacobs & Grainger (1992)	Reicher-Wheeler Lexical decision	Localized	Interactive
Serial search and verification	Paap et al. (1982)	Lexical decision	Localized	One-way
Parallel coding	Carr & Pollatsek (1985)	Reicher-Wheeler Lexical decision naming	Localized	One-way
Fuzzy logical	Massaro & Cohen (1991)	Reicher-Wheeler	Localized	Interactive
Dual route	Coltheart & Rastle (1994)	Lexical decision naming	Localized	Interactive
	Grainger & Jacobs (1994)	Reicher-Wheeler	Localized	Interactive
	Colthart et al. (2001)	Lexical decision naming	Localized	Interactive

Table 1.1 Adapted from Table 1 in Jacobs and Grainger 1994. Only models designed for the WSE are shown. Rumelhart and Siple (1974)'s logogen model was described as explaining the WSE in Jacobs and Grainger's table. However, a close look at Rumelhart and Siple's original paper shows that the logogen model is a "sophisticated guessing" model based on signal probability and "made to account for word frequency effects, effects due to letter transition probabilities, and effects due to physical similarity of character strings to one another". Neither the computational model itself or the test experiment described in their paper has any mention of nonwords, pseudowords, or how they are processed compared to words. Therefore, the logogen model is not included here. Besides, Coltheart, Rastle, Perry, Langdon, and Ziegler (2001), Davis (2010) and Grainger and Jacobs (1994) are added.

view towards word recognition, models summarized in Table 1.1 have received other criticism. Take the Interactive Activation Model for example. The Interactive Activation Model postulates that words are identified on the basis of information obtained from separate letter-position channels, while Mewhort and Johns (1988) argued that extra-letter information is also essential by showing a reduced WSE when words were presented in mixed-case letters and identification of letters without producing a WSE when the letters of a word were rotated 180 degrees. Also, when attempting to explain the word superiority over isolated letters in pattern masked

presentation, the Interactive Activation Model emphasized the role of mask contours that overlay the positions of letters in each stimulus, while Jordan and de Bruijn (1993) suggested that the role of flanking mask contours should also be taken into account. In their study, a word advantage was obtained only when more flanking mask contours were shown with isolated letters than with words; when no flanking mask contours were presented, the word advantage was removed or reversed.

Indeed, each model has its strengths and limitations. The greatest contribution of the WSE towards our understanding of letter and word recognition, is the 'interactive' feature, which relates to the second pair of distinction in theoretical construction in word recognition, i.e., one-way relay versus two-way interaction. Specifically, this pair of distinction concerns whether results of information processing can only feed forward from one layer to its upper layer as in a multi-layer localized hierarchy, from one localized module to the next module as in a multi-module distributed network, or there exist two-direction pathways to enable feed back to a lower layer or a previous module. McClelland and Rumelhart (1981)'s Interactive Activation Model is the first to use this two-way interactivity to account for the WSE. Specifically, this model postulates that words are more familiar to viewers and this familiarity at the top layer in its three-layer structure can feed back towards the intermediate letter level which can then feed back towards the letter feature level at the bottom and therefore benefit identification performance; in contrast, identification of novel letter strings like pseudowords and nonwords receives no such facilitation. This two-way interactive account is also consistent with the characteristics of neural organization that there are usually more (at least as many) feeding-back neural connections as feeding-forward ones and a given cell's receptive field for feedback is usually broader than its receptive field for feed forward (see e.g., Kandel & Schwartz, 1985; Mountcastle & Steinmetz, 1989; Posner &

Carr, 1992). McClelland and Rumelhart's idea has been the most influential in explaining the WSE in that not only the later developments belonging to the same category (including Jacobs & Grainger, 1992, and McClelland, 1991) but also models under other categories (such as the dual-route processing model, Grainger & Jacobs, 1994) are all based on the fundamental architecture of the original Interactive Activation Model. Besides, the fuzzy logical model (Massaro & Cohen, 1991) also acknowledges the influence of the context in which letter occurs on its perception.

A second contribution of the WSE towards our understanding of letter and word reading is that it led to the proposal of dual-route processing. The phenomena that skilled readers can pronounce non-existing pseudowords in a naming task and that readers can discriminate pseudowords more accurately than unpronounceable nonwords in a Reicher-Wheeler task suggest that there exist two routes from print to phonology or orthography. Under the lexical route, a learned word, with its phonological and orthographic properties, is represented as an entry in a mental lexicon which can be directly retrieved from its printed form; under the non-lexical route, however, pronunciation and visual identification of pseudowords can be achieved via readers' reference to a system of spelling and pronunciation rules.

## 1.3 Some other well-known effects in word recognition and their interactions with WSE

### 1.3.1 Word Frequency Effect

Apart from lexical status, stimulus properties in other respects have also been investigated to help with better understanding of word processing. These threads of research led to the finding of some other well-known effects in word recognition,

among which are the word frequency effect, the word length effect, and the orthographic neighbourhood size effect. Below is a brief introduction of these effects and how they interact with the word superiority effect.

The Word Frequency Effect research has heavily depended on the lexical decision task. It refers to the phenomenon that participants respond more quickly to higher frequency words than to lower frequency word when they are asked to decide whether a target stimulus is a word or not. (e.g., Borowsky & Besner, 1993; Dobbs, Fredman, & Lloyd, 1985; Forster & Chambers, 1973; Monsell, Doyle, & Haggard, 1989; Rubinstein, Garfield, & Millikan, 1970; Taft, 1979). Various models have been proposed to account for the Word Frequency Effect which can be categorized into two groups, those arguing that word frequency plays a fundamental role in the activation of mental representations and those advocating that the Word Frequency Effect is post-lexical in nature. Examples of the first group of models include the Serial Search Model (e.g., Forster, 1976; Forster & Bednall, 1976), the Parallel Input Serial Analysis Model (Allen & Madden, 1990), the Parallel Distributed Processing Model (e.g., Allport, 1985; Seidenberg & McClelland, 1989), and the Logogen Model (Morton, 1969). The former two models characterize the mental lexicon as a list of entries in order of occurrence frequency with the highest at the top and the lowest at the bottom so that higher frequency words are encountered before lower frequency word when the mental lexicon is searched and compared against; the latter two models share the fundamental assumption that activation of lexical representations is modulated by word frequency so that words of higher frequency reach the activation threshold more quickly than those of lower frequency and thus faster decision. Representative post-lexical model of the Word Frequency Effect is the two-stage Activation-Verification Model (e.g., Balota & Chumbley, 1984; Becker, 1976, 1985; Paap, McDonald, Schvaneveldt, & Noel, 1987;

Paap & Johansen, 1994), which postulates that activated candidates containing matching features of the target stimulus are submitted to the verification process in order of frequency with the more frequent candidates submitted earlier and thus more rapid identification.

Although it remains an ongoing dispute among psychophysical studies that at what stage word frequency exerts its effect (for recent studies, see Allen, Smith, Lien, Grabbe, & Murphy, 2005) and Paap, Johansen, Chun, & Vonnahme, 2000), studies using the electrophysiological technique to monitor the time course of brain activations have obtained evidence that the Word Frequency Effect tasks place after the lexical processing starts (e.g., Hauk & Pulvermüller, 2004; Sereno, Rayner, & Posner, 1998). Relevant to the research topic of the present thesis, it is important to note that word frequency has been found to interact with lexicality to affect identification performance. Specifically, word-nonword difference is larger for high-frequency words compared to low-frequency words (e.g., Stanners, Jastrzembski, & Westbrook, 1975). Indeed, the finding that word frequency has an impact on the size of the WSE but not its presence also supports a post-lexical view of the Word Frequency Effect.

### 1.3.2 Word Length Effect

Apart from word frequency, word length (measured as number of letters) has also been shown to have an impact on word identification performance. A facilitatory effect of word length was reported in Samuel and colleagues' classic study using 1-4 letter words including pronouns (Samuel, Van Santen, & Johnston, 1982). They observed better identification performance for longer words than for shorter words, thus 'We is better than I but worse than you or them'. However, when words containing more than four letters are tested, an inhibitory effect appears instead (see e.g., Balota, Cortese, Marshall, Spieler, & Yap, 2004; Hudson & Bergman, 1985). New, Ferrand, Pallier, and

Brysbaert (2006) investigated the impact of word length on word recognition by using a substantially large stimulus set featuring a comprehensive range of word length (33,006 words from the English Lexicon Project with word length ranging between 3-13 letters, see Balota, Yap, Cortese, Hutchison, Kessler, Loftis, Neely, Nelson, Simpson, & Treiman, 2002 for details). They measured the lexical decision response times and the results revealed a U-shaped curve of word length effect, i.e., facilitatory for shorter words (3-5 letters), null for midrange (5 to 8 letters) and inhibitory for longer words (8 to 13 letters). For pseudowords or nonwords, effect of word length has been shown to be either null (e.g., 1-4 letters examined in Samuel et al., 1982) or inhibitory (e.g., 4-12 letters in Hudson & Bergman, 1985; 3-13 letters in New et al., 2006). There is little explanation in the literature for the facilitatory effect observed among shorter words. The null and inhibitory effects of word length have typically been accounted for by the notion of 'parallel vs sequential processing'. Specifically, New et al. (2006) argued that words of intermediate length (5-8 letters) not only have higher type frequency, being more often encountered in everyday reading than shorter or longer words, but also have higher chances of being processed after one single fixation during reading in contrast to the more often skipped shorter words and the more re-fixation-demanding longer words. In consequence, orthographic information of 5-8-letter words is more likely to be processed in a parallel manner whereas orthographic information of longer words tends to be analyzed sequentially in a left-to-right cycle. Indeed, the inhibitory effect of word length on wordlike letter strings has also been typically considered as suggesting that parallel processing is exclusive to linguistic stimuli and serial processing is the only route available to non-linguistic stimuli.

It is important to note that the word length effect is often found in interaction with the visual field effect. When appearing alone, the visual field effect refers to the

observation that words presented in the right visual field (RVF) are usually identified better than words presented in the left visual field (LVF) (e.g., Moscovitch, 1973; Springer, 1977; White, 1969). When visual field and word length both manipulated, it is typically found that word length variations affect word recognition performance only in the left visual field (LVF) but not in the right visual field (RVF) (e.g., Bruyer & Janlin, 1989; Bub & Lewine, 1988; Chiarello, Maxfield, Richards, & Kahan, 1995; Ellis, Young, & Anderson, 1988; Eng & Hellige, 1994; Eviatar & Zaidel, 1991; Iacoboni & Zaidel, 1996; Young & Ellis, 1985.). The prevailing interpretation for this interaction in the literature is also related to the assumption of 'parallel/serial processing' distinction. Specifically, it is a well-established finding that extrafoveally presented stimuli in either visual field initially project to the hemisphere contralateral to the stimulated visual field; therefore, the observation that length variations affect word identification performance only in the LVF but not in the RVF indicates that the LH is more specialized and more efficient than the RH in word processing by analyzing information in a parallel manner.

However, the above-mentioned arguments are questionable in the following ways. Firstly, there is evidence that the parallel and the serial mechanisms are not exclusive of each other, namely, either can exert its effect for a particular word stimulus. Jordan and colleagues assessed the 'parallel/serial processing' in both single word and sentence reading (Jordan, 1995; Jordan, Thomas, Patching, & Scott-Brown, 2003a; Jordan, Thomas, & Patching, 2003b). They found that degrading exterior letters (beginning and ending letters) impaired reading rate more than degrading interior letters and letter discrimination accuracy was greater at the exterior letter positions than at the interior letter positions, forming a U-shaped curve of performance pattern. Although these behavioural measures provide no direct evidence that exterior letters are temporally analyzed before interior letters, the U-shaped curve indicates that the

beginning and the ending letters of a word are equally easier to identify than and equally more important in determining reading performance than interior letters. Indeed, the U-shaped curve of performance pattern implies the possibility that orthographic information analysis starts parallel for letters in the 'outside' positions of a word before moving towards the 'inside' of a word. Secondly, Jordan et al. obtained identical U-shaped curves for both words and nonwords with the WSE in each letter position, which indicates that this outside-in pattern of processing is visuoperceptual in nature, irrespective of stimuli's lexical status. In addition, identical U-shaped curves were found in both visual field whereas only the RVF presentation produced a WSE. This is consistent with the view that the LH is more specialized in language processing. Nevertheless, it clearly does not support the argument that the LH advantage in word processing is due to that it uses a parallel mode of orthographic analysis whereas the RH a serial mode.

### 1.3.3 Orthographic Neighbourhood Size Effect

Another well-known finding in word recognition literature is the Orthographic Neighbourhood Size Effect. For a given word, its orthographic neighbourhood size refers to the number of words that can be created by changing one single letter of that word (Coltheart, Davelaar, Jonasson, & Besner, 1977). Using the lexical decision and naming tasks, researchers have shown that the orthographic neighbourhood size has a facilitatory effect on participants' response times, although the effect seems to be restricted to low-frequency words (for reviews, see Andrews, 1989, 1997; Grainger, O'Regan, Jacobs, & Seguí 1989; Grainger, 1992; Perea & Rosa 2000). However, this facilitatory effect of neighbourhood size presents challenge to word recognition models that involve the process of searching through a set of possible candidates before the matching lexical entry is activated. As Perea and Rosa (2000) noted, such process of

lexical access would be slowed down by having to search through and compare against a greater number of competing candidates or neighbours. Indeed, some researchers have doubted on the use of the lexical decision as a tool for assessing the effects of orthographic neighbourhood size as participants can respond correctly to the lexical status of a low-frequency word on the basis of incorrect retrieval of a more frequency neighbour (e.g., Perea & Rosa, 2000; Pollatsek, Perea, & Binder, 1999).

Recall the interaction between word length and visual field mentioned above. There is evidence that this interaction is only true for words with low neighbourhood size. Specifically, for words with low orthographic neighbourhood size, word length affected lexical decision response times in the LVF but not in the RVF; in contrast, when words had large orthographic neighbourhood size, neither visual field was affected by word length (e.g., Lavidor & Ellis, 2002; Mano, Patrick, Andresen, Capizzi, Biagioli, & Osmon, 2010).

#### 1.3.4 Summary

This section briefly introduced the Word Frequency Effect, the Word length Effect, and the Orthographic Neighbourhood Size Effect and how they contribute to understanding the processes involved in word recognition. It is important to note that these effects may interact among themselves and with the WSE. The influence of word frequency and word length has been individually mentioned above. However, there exists evidence of a three-way interaction. For example, although word frequency is often reported to reduce the size of the WSE rather than eliminating it, Peterzell, Sinclair, Healy, and Bourne Jr (1990), using a fixed set of three-letter stimuli, obtained the typical WSE for the higher-frequency word ('the') but not for the lower-frequency words ('tee', 'tie', and 'toe'). Peterzell et al. attributed the WSE to bias rather than discriminability, arguing that participants exhibited a bias to perceive the words in their

experiment as 'the' (i.e., there was a bias to perceive 'h' in the 't\_e' stimulus presentations). However, they provided no further explanation as to what caused the visual bias towards a higher-frequency word, which is not observed in other studies (e.g., Samuel et al., 1982). Possibilities include very short stimulus exposure duration and very long backward masking. Indeed, although the stimulus exposure duration was not reported, Peterzell et al. used backward masking for 1000 ms which may have disrupted the extraction of fine-scale information at the stroke and letter levels; instead, participants had to rely more on the coarse-scale supraletter information and therefore tended to respond with a higher frequency orthographic neighbour. This suggests that lexicality not only interacts with other properties of words like frequency, length, and orthographic neighbourhood, it is also influenced by other factors employed in a particular experiment to affect word recognition.

## 1.4 The Reicher-Wheeler task

Numerous studies have shown that experimental task or paradigm plays a crucial part in psychological research, especially in language-related areas. Although some robust effects in word recognition research may be obtained across tasks, such as the WSE, more often they are task- or paradigm-sensitive. This is mostly due to various cognitive demands imposed by different experimental tasks. Specifically, a word has multiple aspects of linguistic properties. Three major linguistic properties of a word are orthographic (visual form), phonological (sound), and semantic (meaning). Different experimental tasks typically emphasize (overtly or covertly) the processing of different aspects of linguistic properties and may cause the discrepancies in results across studies, despite the same stimuli set.

Recall that when the Word Frequency Effect, the Word Length Effect, and the

Orthographic Neighbourhood Size Effect were introduced above, they were all associated with the lexical decision or naming task. In the lexical decision task, participants are presented with words or nonwords one at a time and asked to decide as quickly as possible whether the target stimulus they have just seen is a word or nonword. The naming task requires participants to read aloud each target stimulus or report the letters contained in a target stimulus if nonwords are involved. The research topic of the present thesis, the WSE, however, has been closely associated with the Reicher-Wheeler task. Indeed, although research comparing how participants respond to words and nonwords dates back to the 1880s (e.g., Cattell, 1886) and the word advantage over nonwords has been observed in other tasks as well (e.g., lexical decision, naming, letter detection, and various types of judgement tasks including old-new/same-different/size judgements), it was until Reicher (1969) and Wheeler (1970) when systematic WSE over single letters, pseudowords, and nonwords was investigated in a paradigm specifically designed to focus on visual processing while suppressing guesswork and use of strategy. Specifically, in the Reicher-Wheeler task, participants are shown target stimuli (single letters, words, or nonwords) one at a time and asked to identify which of the two following alternative choices is the target stimulus they had just seen. The reasons why the Reicher-Wheeler task has since been considered the most appropriate task for investigating the WSE are as follows.

Firstly, the Reicher-Wheeler task presents participants with a scenario close to everyday reading in the sense that all target stimuli are shown in a passive viewing mode and even the offline task of choosing between the two alternatives requires attention to targets' orthography only. On the contrary, many other tasks used in word recognition research are online tasks, imposing external cognitive demands apart from the 'viewing' itself. For example, the lexical decision task involves extra decision

making and the naming task demands explicit phonological articulation, which are not natural of everyday reading. There are also some other tasks which seem to involve 'passive' viewing like the Reicher-Wheeler task. For example, in the semantic categorization task, participants are shown a prime word and a target word on each single trial and are asked to decide whether the prime and the target are of the same semantic category; or in a similar vein, the semantic or phonological similarity judgement task asks participants to decide whether a target is semantically or phonologically related to its prime. These tasks all demand particular attention to the semantic or phonological properties of target stimuli and induce extra decision making and calculations. Indeed, the orthographic processing involved in passive viewing conditions may not remain the same when explicit workload of phonological or semantic processing is imposed; besides, participants' performance on post-lexical decision making and judgement does not provide direct answers as to whether letters in a word context are more visually perceptible compared to in other non-word contexts.

Another major reason why the Reicher-Wheeler task is more appropriate in assessing the WSE is due to its stringent design in order to rule out the use of guess work based on orthographic knowledge or the use of strategy. Specifically, as shown in Figure 1.1, in the Reicher-Wheeler task, the two alternatives for each target stimulus are always of the same stimulus type as the target, i.e., two word alternative choices for a word target, two nonword alternative choices for a nonword target, two pseudoword choices for a pseudoword target, and two single letter choices for a single letter target. Besides, the two alternatives differ only by one letter in the same position. The letter position where the two alternatives differ is called the critical letter position, the two letters in that position are called critical letters and letters in the remaining positions are called non-critical letters. As a consequence, for the critical letter in a particular target

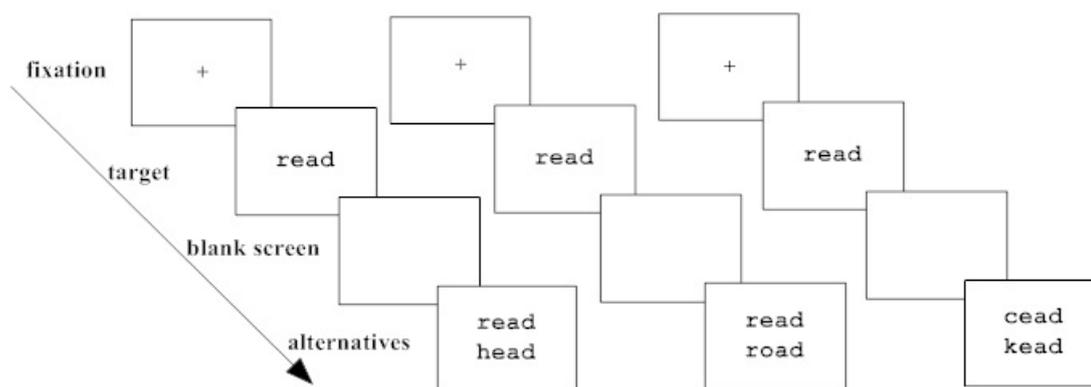


Figure 1.1. Three example trials on the Reicher-Wheeler task. Boxes symbolize display screen. The series of boxes to the left illustrate a word trial with the first letter position of the target word ('read') as the critical letter position in which the two alternatives differ. The series of boxes in the middle shows when the second letter position of the target word as the critical position. The series of boxes to the right exemplifies how letters in a particular letter position (the first letter in this case) of a matched pair of words can be altered to make a matched pair of pseudowords.

word, participants cannot base the correct choice merely on their orthographic knowledge since both letters can be combined with the non-critical letters to form a valid word, as shown in Figure 1.1. This is what distinguishes the Reicher-Wheeler task from any ordinary two-alternative forced choice paradigm (often abbreviated to the 2AFC paradigm). Indeed, the lexical decision task can also be categorized under the 2AFC paradigm. However, participants can make a correct response based on incorrect identification of the test stimulus. For instance, if the target word 'read' was presented, it is possible that participants perceived it as 'head', 'road' or 'real' and decided they had just saw a legal word, which would still be registered as a correct answer. Similar problem persists even for some offline tasks which emphasize the orthography of stimuli. A typical example is the same-different judgement which asks participants to judge if a target stimulus is the same as or different to a prime stimulus they have just seen. Participants can make a correct response even when they only see partial contents of the prime and(or) the target and are just guessing.

For the above reasons, the Reicher-Wheeler task will be the task used in the present thesis to investigate the WSE in Chinese.

## 1.5 Visuoperceptual factors in the WSE

The above section explains why the Reicher-Wheeler task is critical to investigation of the WSE. It is important to mention that apart from the experimental task, the visuoperceptual characteristics of stimuli and stimulus presentation may also have an impact on the WSE and more generally word recognition. The first such visuoperceptual factor is the retinal image size of stimuli. By using letters with a horizontal visual angle of 0.2 and 0.25 degrees while manipulating interletter space, Eriksen and colleagues showed that the time taken to identify a target letter decreased when interletter distance was increased from 0.06 to 1.0 degrees, i.e., when four-letter size increased from 0.98 to 2.3 degrees for 0.2-degree letters and from 1.18 to 2.5 degrees for 0.25-degree letters (Eriksen & Eriksen, 1974; Eriksen & Hoffman, 1972). Using three-letter stimuli, Purcell, Stanovich, and Spector (1978) observed that words were reported more accurately than nonwords when stimuli subtending less than 0.6 degrees; however, they found that the WSE was removed when the same stimuli were presented in a visual angle of over 2 degrees. Another important visuoperceptual factor in the WSE include visual field of presentation. The influence of presentation visual field on word recognition has been touched upon in Section 1.1.3 Specifically, the RVF seems to have an advantage over the LVF in that participants' performance on words presented in the LVF has been shown to be affected by variations in word frequency, word length and orthographic neighbourhood size whereas performance on words presented in the RVF largely remain unaffected. In a similar vein, there is evidence suggesting that the visual field of presentation also interacts with the WSE. For example,

Jordan, Patching, and Milner (2000) found that words were identified with greater accuracy than nonwords when they were presented in the RVF whereas words presented in the LVF produced similar level of identification performance as nonwords. The effect of visual field on behavioural and electrophysiological responses will be elaborated in Chapter 6. Other visuoperceptual factors that affect the WSE include visual masking, which will be discussed in Chapter 4 and format distortion (e.g., case alternation, see Bruder, 1978; Jordan, Redwood, & Patching, 2003).

## 1.6 Summary

This chapter lays the background of the entire thesis by introducing the research topic to be investigated, which is the Word Superiority Effect (WSE). Firstly in Section 1.1, the WSE was defined as the phenomenon that when given the task of identifying which of two alternative letters was contained in a briefly presented stimulus, readers are more accurate when the letter occurred in a word than in a pseudoword, and occurred alone (e.g., ###d, ###k).

Section 1.2 summarizes the two major contributions of the WSE towards understanding and theoretical construction of word recognition. The first contribution is that the WSE sheds light on the 'interactiveness' in the visuoperceptual processing of a word, namely, there exist two-direction pathways to enable outputs of information processing to feed back to a lower layer as in a multi-layer localized hierarchy or to a previous module as in a multi-module distributed network. The second major contribution of the WSE is that it led to the proposal of dual-route processing in alphabetic reading. The pseudoword advantage over nonwords observed when investigating how context affects letter identification suggest that there exist two routes from print to phonology or orthography, namely, the lexical route where a learned word

is represented as an entry in mental lexicon, and the non-lexical route where pronunciation and visual identification of pseudowords can be achieved via readers' reference to a system of spelling and pronunciation rules.

Section 1.3 then briefly mentioned several other important effects in word recognition and how they interact with the WSE. Word frequency is often reported to affect the size of the WSE; word length variations has been associated with the absence or presence of the WSE with no WSE for very short words (e.g, one or two-letter words). There also exists evidence of a three-way interaction among them so that for three-letter short words, the WSE was only observed for higher-frequency words but not for lower-frequency ones. One explanation for the absence of the WSE in this case is that the certain factors, duration of stimulus presentation and backward masking in particular in this case, intervened with visual information processing at fine-scale levels to an extent that participants were biased to respond with candidates with more familiar coarse-scale information.

## **Chapter 2. General Introduction II: The Word Superiority Effect in Chinese character recognition**

The WSE is one of the best-established findings in reading English and other alphabetic languages. Indeed, the question can be raised as to whether this facilitatory effect of lexical context on perception of sublexical components exists in non-alphabetic language reading. Chinese is used by the largest population in the world and is dramatically different from English in various aspects. As the second part of the General Introduction, this chapter will lay the language background for the research topic of the thesis, the WSE in Chinese, by providing a brief introduction to the Chinese language (including its writing system, its distinct features and the making of pseudocharacters and noncharacters) and an overview of the WSE research in Chinese in a similar structure as Chapter 1 for cross-linguistic comparisons.

### **2.1 The Chinese language**

#### **2.1.1 Writing units of Chinese: stroke, radical, and character**

It should be pointed out that nowadays Chinese exists in two scripts, the traditional script and the simplified script. The traditional Chinese script remains the same as it was before 1950 and is now used by Chinese speakers resident outside of mainland China, mainly including Hong Kong, Taiwan, and Macau. The simplified script is the outcome of the character-simplification movement led by the government in mainland China between 1950-1964 (see webpage of China's Ministry of Culture, [http://www.mcprc.gov.cn/ggfwnew2011/zgwh/ys/wzysf/201111/t20111121\\_137480.html](http://www.mcprc.gov.cn/ggfwnew2011/zgwh/ys/wzysf/201111/t20111121_137480.html)) and has since been the official Chinese script in mainland China. It is also the

Chinese script that will be addressed throughout the present thesis<sup>2</sup>.

The smallest writing unit of Chinese is stroke, which is traditionally defined as a continuous movement when pen set to paper (e.g., Tseng, Chang, & Chen, 1965). Strokes combine in conventional patterns to form radicals, which in turn are components of characters, the basic writing unit of Chinese. Each character is a compact square shape consisting of one or more radicals, thus making simple characters and compound characters respectively. Being simple or compound is only a simplistic way of describing character structure. According to *Analysis and Explanation of Characters*<sup>3</sup>, characters can be classified into six categories based on the nature of their formation rules. They are pictograms, simple ideograms, ideogrammatic compounds, phonetic-semantic/semantic-phonetic (SP/PS) compounds, phonetic loans, and derivative cognates, among which the first four categories are common in modern Chinese. It is important to note that left-right structured SP/PS compound characters are most popular, taking up approximately 81% of modern Chinese vocabulary (Chen & Zhang, 2008).

### 2.1.2 Distinctions between Chinese and English writing

There might be an argument that the stroke-radical-character hierarchy in Chinese writing is comparable to the feature-letter-word hierarchy in English. Indeed, similar to the fact that items from the 26-letter alphabet, each typically decomposed into letter features, form English word, there are also a fixed number (201, as defined by the most recent edition of *Xinhua Dictionary*, 2004) of radicals and items from this pool then group into characters by conventional rules. In this sense, radicals may seem comparable to letters and characters to words. However, this superficial similarity is not

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<sup>2</sup> The terms 'Chinese' and 'Chinese characters' will hereafter refer to the simplified Chinese and its characters exclusively. Characteristics of the simplified characters in terms of their formation origins and overall spatial configurations are also shared by characters in the traditional Chinese script.

<sup>3</sup> *Analysis and explanation of characters* was the masterpiece work of the ancient Han-dynasty Chinese scholar Shen Xu and was finished between 100-121. It is the first Chinese dictionary with systematic radical index.

supported by the following distinctions.

First of all, unlike letters adhere in linear array to form words, Chinese characters are made of radicals in various two-dimensional spatial configurations. More specifically, radicals not only occur left or right to each other but also top or bottom to each other; when a character involves more than two radicals, there is often a middle position, as in left-middle-right (e.g., 鸿, 储, 树) or top-middle-bottom structures (e.g., 惹, 鼻, 意), or even a top-left/bottom-right (e.g., 新, 涅). There also exist certain unique circular-like radicals in Chinese which occur at the same level both horizontally and vertically as other radicals, namely, centering on the same or close coordination in a two-dimensional layout as the remaining radicals in the character (e.g., 边, 仄, 句, 冈, 凶, 区, 回). It is mentioned above that SP/PS compound characters are most frequent, taking up more than 80% of modern Chinese vocabulary, and therefore will be the type of character structure used in Experiments 2-5 in the present thesis. It should be pointed out that 'left-right structured' is rather a simplified way to roughly describe how the two component radicals adhere to each other in this case and by no means equals the pure linear structure of English words. In fact, the two radicals often closely interact with each other in a way that the strokes of either radical extend into the blank space of the other to make the character an integrated whole.

The two-dimensional square shape of Chinese characters leads to a second distinctive feature of Chinese writing, namely, radicals appearing in various sizes. Although English letters vary in shapes, they share the feature of having a 'base core' along the same horizontal level and the major difference lies in whether there is a part extending from the 'base core' and if yes whether the extension is ascending or descending. In consequence, English letters are similar in their width except a few being slightly thinner or wider than average (i.e., i, l, m, w); more letters make a longer linear

string and thus longer word length. In contrast, to accommodate the overall square compactness of characters, radical size variation not only happens to different radicals but also applies to some radicals themselves. Take SP/PS compound characters for example. The radical on the left is usually thinner, sometimes shorter at the same time, than the radical on the right in a left-right structured SP compound (e.g., 清) and vice versa in a left-right structured PS compound (e.g., 判); the radical at the top is typically shorter, most likely also thinner, than the radical at the bottom in a top-bottom structured SP character (e.g., 崗, 筒) (e.g., Wang & Ching, 2005; Zeng & Zhou, 2001). More importantly, some radicals can occur on the left as the semantic radical in SP characters as well as on the right as the phonetic radical in PS characters. Therefore, their sizes vary accordingly, being smaller on the left in SP characters and larger on the right in PS characters.

Apart from the above, Chinese characters and English words are distinct from each other also in their phonological and syntactic properties. In phonographic languages like English, a letter (e.g., 'i') or a letter combination (e.g., 'igh' as in 'high') represents a phoneme (speech sound, smallest segmental unit of sound) and words feature assembled phonology of constituent phonemes. However, in the logographic Chinese, radicals are all morphemes (smallest semantically meaningful unit in a language). When single or multiple radical(s) make(s) a character, an arbitrary sound is designated to this character. Moreover, Chinese characters and English words are not completely equivalent at the syntactic level. It is common between alphabetic languages that for a word in one language there is a counterpart word in another (e.g., between English and French). However, in many cases the corresponding Chinese expression for an English word is a phrase rather than a single character (see e.g., Chen, 1992). To be more specific, some Chinese characters never appear alone; instead, it is conventional

for them to adhere with certain other characters to form multi-character phrases. For example, the Chinese counterpart for the English word 'apple' is '苹果'. The first character '苹' means 'apple' and second character '果' represents 'fruit', the generic category of apple. Although both characters are meaningful, the first character '苹' (apple) cannot stand alone. Examples in contrast include Chinese names for fruit and nut, which are '水(水)果(果)' and '坚(坚)果(果)' respectively. Although both names are also two-character noun phrases which end with the same generic name '果 (fruit)' as in '苹(apple)果(fruit)', '水'(water) and '坚'(hard) are independent characters which can appear alone or in other multi-character phrases. Therefore, the phenomenon that words in English (or other alphabetic languages) do not always correspond to characters in Chinese at the syntactic level is a natural feature of the Chinese language rather than due to any translation issue. It is worth mentioning that a multi-character noun, verb, or adverb phrase is traditionally referred to as a 'word' in Chinese. Some Chinese researchers followed this convention and used the term 'word' to refer to such phrases in their publications, which is misleading (e.g., Chou & Shillcock, 2001; Fang, 1994, 2003).

### 2.1.3 Pseudocharacters and noncharacters

It was introduced in Section 2.1.1 that the positioning of a radical in compound characters is highly conventional. Some radicals can only take place in a certain position of all compound characters (e.g., '亻' and '本' as in '体') whereas some other radicals enjoy greater flexibility (e.g., '口' as in '吕' and '品'). This positional regularity of radicals makes it possible to produce pseudocharacters and noncharacters in Chinese. Specifically, a non-existing combination of radicals in their regular positions will make a pseudocharacter and a noncharacter can be existing or non-existing combination of

radicals with at least one radical in its irregular position. For example, `体' (body) and `棍' (stick or bar as noun) are both left-right structured compounds. There are four component radicals involved altogether, i.e., `亻', `本', `木', and `昆', among which only `木' is seen on either side of a left-right structured compound character whereas the other three can only occur in the positions they are in the two example characters. Radical on the left in either of these two characters (`亻' and `木') cannot go along with the radical on the right in the other (`本' and `昆'). Therefore, by swapping radicals on each side between the two characters we can make two pseudocharacters, i.e., `亻 昆' and `木本'. Moreover, since `亻', `本', and `昆' all have fixed positions, noncharacters can be produced by placing any of them in their impossible position in the context of their original character or a new radical combination, for example, `本亻', `本木', `本昆', `昆亻', `木亻', `昆木', `昆亻', or `昆本'.

## 2.2 The WSE in Chinese character recognition

### 2.2.1 Evidence of the WSE in Chinese character recognition

Research in the field of Chinese character reading dated back to the 1920s and they were mostly concerned about the effect of reading direction on reading performance (e.g., Chen & Carr, 1926; Chen, 1929a, 1929b; Tsai & Abernethy, 1928). It was not until the 1980s that Chinese researchers started to investigate the WSE in Chinese character recognition (e.g., Cheng, 1981; Cheng & Yang, 1989). Compared to the WSE research in English, the WSE research in Chinese has the following characteristics.

Firstly, the WSE research in Chinese does not compare to the WSE research in

English in terms of the quantity and the depth of published studies. As introduced in the previous chapter, there exists a 'golden' period for the WSE in English starting from the classic work of Reicher (1969) and Wheeler (1970) till the late 1990s. During this period, researchers showed intense interest in the phenomenon. A comprehensive range of aspects of the WSE were investigated, including whether and how it is affected by visuo-perceptual factors (e.g., exposure duration, stimulus size, masking) and other established effects in word recognition (e.g., Word Length Effect, Word Frequency Effect, Orthographic Neighbourhood Size Effect) and more than a dozen of theoretical models were proposed to explain mechanism under the WSE (refer back to Sections 1.2, 1.3, 1.4, and 1.5 for details). In contrast, the first published work on the WSE in Chinese character recognition did not appear until the early 1980s (Cheng, 1981). Since then, only several other studies have specifically investigated the issue (e.g., Cheng & Yang, 1989; Kao, Chen & Chen, 2010; Mattingly & Xu, 1994; Mok, 2009; Yang & Cheng, 1999). More often, characters and pseudocharacters/noncharacters are compared against each other in studies aiming at other research topics (e.g., Chen, Allport & Marshall, 1996; Cheng & Huang, 1995; Li, Fu, & Lin, 2000; Peng & Li, 1995; Shu & Anderson, 1999; Taft & Zhu, 1997). Apart from the quantity of designated studies, research in the WSE in Chinese also lacks in experiment stringency (task, stimulus setting, etc.) and in the range of factors examined relevant to the issue, which will be elaborated on below and in Chapter 4.

Secondly, in contrast to that fact that a robust WSE has been consistently reported in English word recognition studies regardless of tasks, research assessing the WSE in Chinese produced mixed findings. Chen (1981) reported the character advantage over pseudocharacters and noncharacters using a two-alternative forced choice paradigm. These studies have used the Interactive Activation Model to explain

their observation. The argument is that Chinese character recognition takes place in a three-layer hierarchic manner similar to that in English word recognition. Specifically, character processing starts with stroke segments and strokes as the bottom layer before it proceeds to radicals at the middle layer and further on to characters at the top layer. It is hypothesized that characters are familiar to readers with representations in the mental lexicon. When the matching entry in the mental lexicon for a particular target character is activated, the outcome of this whole-character activation feeds back to lower layers and benefits activation at the levels of strokes and radicals. Consequently, in data-limiting viewing conditions (i.e., brief presentation in the present case), it is easier to identify characters compared to pseudocharacters or noncharacter which do not benefit from top-down facilitations. Nevertheless, the opposite pattern to the WSE has also been observed in some other studies. For example, Cheng and Huang (1995) and Shu and Anderson (1999) found that participants made fewer mistakes for noncharacter stimuli relative to pseudocharacter stimuli; Li et al. (2000) and Peng and Li (1995) even observed faster and more accurate response to noncharacters compared to both real characters and pseudocharacters. It is important to mention that all these four studies used the lexical decision task and attributed the noncharacter advantage in response time and accuracy to the fact that radical position regularity was violated in noncharacters. Since noncharacters are made by combining two radicals each in a position they cannot occur in normally, participants may easily make the lexical-or-nonlexical decision based on this prominent feature without actually seeing or even making the effort to see much of detailed visual contents.. This resonates with the point made in Section 1.4. On the other hand, the noncharacter advantage observed in the lexical decision task sheds light on the initial processes involved in perceiving characters and character-like stimuli, namely, information at more coarse-scale levels

(overall outline of and inter-radical spatial relationships in a character or character-like stimulus in particular) is extracted and plays a more important role in very early stages of character processing. This implication disagrees with the argument of the Interactive Activation Model that word perception begins at the level of letter features, or at the level of stroke segments and strokes as proposed by Cheng (1981) (refer back to Section 1.2 for more criticism of the Interactive Activation Model).

It was explained above in Section 2.1.2 that the term 'word' in Chinese refers to a multi-character phrase of any part of speech, i.e., noun, verb, adjective, adverb, conjunction, or preposition and some Chinese researchers followed this Chinese convention in the titles of their publications. In consequence, simply searching for titles relevant to the research topic of the WSE in Chinese can produce misleading results. For example, Hue (1989), Mattingly and Xu (1994), and Mok (2009) all used titles that claimed to investigate the 'word superiority' in Chinese, however, a closer look into the articles revealed that they all used multi-character phrases as stimuli rather than single characters.

## 2.2.2 Chinese WSE and other well-known effects in character recognition

### 2.2.2.1 Word Frequency Effect

Unlike the literature investigating the Word Frequency Effect in English which consistently reported faster and more accurate responses for higher-frequency words than for lower-frequency words, studies using Chinese characters produced different results depending on the experimental task employed. Studies using naming and lexical decision tasks typically had similar findings as that in the English literature, namely, faster and more accurate responses for higher-frequency characters than for lower-frequency characters (e.g., Gao, Zhong, & Zeng, 1995; Peng & Wang, 1997; Yu & Cao, 1992). Similar facilitatory effect of character frequency has also been observed in eye

movement studies (e.g., Yan, Tian, Bai, Rayner, 2006). However, the opposite performance pattern has been reported in studies using a different task. For example, Cheng (1981) used a two-alternative forced choice paradigm and observed greater identification accuracy for lower-frequency characters compared to higher-frequency characters, which accordingly led to a reduced character superiority over pseudocharacters for higher-frequency characters.

#### 2.2.2.2 Word Length Effect

Due to the fact that each character is a compact square shape, the length effect does not apply to Chinese character reading. There exist some publications whose titles claimed that they were designated to examining the Word Length Effect in Chinese. However, it was noted above that the term 'word' in Chinese refers to multi-character phrases (meaning of the terms 'character' and 'word' was defined in Section 2.1.2). These studies actually investigated whether and how the number of characters affects Chinese word reading rather than character reading and have typically reported increasing response times with increasing character number (e.g., Chou & Shillcock, 2001; Fang, 1994, 2003; Hue, 1989; Yan, Kliegl, Richter, Nuthmann, & Shu, 2010).

Indeed, it might be argued that although the visual complexity of Chinese characters does not reflect on the length of linear arrays, it can be measured by the number of strokes contained in the two-dimensional square space. It has been observed across experimental tasks that characters with fewer strokes produce faster and more accurate responses than characters with more strokes; more importantly, this stroke number effect is independent of other factors like character frequency (e.g., two-alternative forced choice: Cheng, 1981; lexical decision and naming: Peng & Wang, 1997; Yu & Cao, 1992). In Cheng (1981), a reduced character superiority was found for characters with more strokes as a result of poorer performance they produced compared

to characters with fewer strokes. There is also evidence that the visual complexity of characters in terms of number of strokes affects eye movement patterns in Chinese reading (e.g., Yang & McConkie, 1999).

### 2.2.2.3 Orthographic neighbourhood size effect

There are very few studies that investigated the Orthographic Neighbourhood Size Effect in Chinese character reading. In contrast to a facilitatory effect associated with English words with large orthographic neighbourhood size (e.g., Andrews, 1989, 1997; Grainger, O'Regan, Jacobs, & Seguí 1989; Grainger, 1992; Perea & Rosa 2000), an inhibitory effect has been reported for Chinese characters with large orthographic neighbourhood size. For example, Li, Bi, Wei, and Chen (2011) and Li, Bi, and Zhang (2010) found slower naming responses to characters with more orthographic neighbours relative to characters with fewer orthographic neighbours. More importantly, it was revealed that the inhibition was observed only when high-frequency neighbours with different pronunciations to target characters were present. Indeed, high-frequency characters are more often encountered by readers and can show greater interference on naming responses to their orthographic neighbours especially when they have distinct pronunciations. However, further investigation is required as the above-mentioned studies found the inhibitory orthographic neighbourhood size effect in Chinese by using the naming task and tackling how orthographic similarity affected the phonological processes rather than the orthographic processes involved in character recognition.

Since the existing literature has used the naming task, it remains unknown whether the Orthographic Neighbourhood Size Effect interacts with the WSE in Chinese.

### 2.2.3 The experimental task

The experimental task employed in an empirical study plays a critical role in determining the perceptual and cognitive workload that is involved or emphasized in processing stimuli and accordingly the result pattern that is eventually obtained. The Reicher-Wheeler task has been shown to be more appropriate in assessing the WSE than other common tasks such as the lexical decision and naming (refer back to Sections 1.4 and 2.2.1). However, none of the existing studies used the Reicher-Wheeler task properly to investigate the WSE in Chinese. As noted in Section 2.2.1, most studies in the existing literature used the lexical decision task and some even observed the noncharacter advantage over characters and pseudocharacters in terms of response time and accuracy (e.g., Cheng & Huang, 1995; Li et al., 2000; Peng & Li, 1995; Shu & Anderson, 1999). These studies attributed the noncharacter advantage to the fact that the radical position regularity was violated in noncharacters. It is hypothesized that participants can make the lexical-or-nonlexical decision more easily based on this prominent feature without actually seeing more detailed visual contents in noncharacter stimuli. Therefore, the finding of noncharacter advantage reflects more on the cognitive task of decision-making rather than on the perceptual identification of stimuli per se. Apart from the lexical decision, the two-alternative forced choice paradigm was also employed by some researchers to assess the WSE in Chinese character recognition (e.g., Cheng, 1981; Cheng & Yang, 1989). Although it sound seemingly similar to the Reicher-Wheeler task, the way it was used in relevant studies made it far less stringent than the Reicher-Wheeler task. Take Cheng (1981) for example. One of its major methodological flaws is that the making of pseudocharacters was not systematic. For the majority of characters, their pseudocharacter counterparts were formed in the same manner as described in Section 2.1.3, namely, by replacing one of the component radicals in each character with another radical to make a nonexisting combination of

radicals; whereas for other characters, their pseudocharacter counterparts were formed by adding an additional radical or even replacing all component radicals, the latter making pseudocharacters completely unrelated to their character counterparts (imagine using `vout' as the paired pseudoword for the word `read'). Besides, stimuli of different spatial constructs were used across conditions, e.g., top-bottom structured pseudocharacters paired with left-right structured characters. Its methodological design may be further contaminated by failing to counterbalance either the proportions of characters of different spatial constructs or the proportions of characters with different critical radical positions. This will be elaborated in the introduction of Chapter 4.

#### 2.2.4 Visuoperceptual factors

As noted above, the WSE research in Chinese does not compare to the WSE research in English not only in terms of the quantity but also in terms of the depth of published studies. This is also reflected in the range of visuoperceptual factors that have been investigated in relation to the WSE in Chinese. Section 1.5 mentioned that researchers have examined whether and how visuoperceptual factors such as exposure duration, stimulus size, masking, visual field, and form distortion affect the presence or size of the WSE using English words as stimuli. In contrast, only the factor of visual field has been reported in the existing literature in relation to the WSE in Chinese. Cheng and Yang (1989) presented character and pseudocharacter stimuli in either visual field (LVF and RVF) and observed greater identification accuracy when characters were presented in the LVF than when presented in the RVF. This LVF advantage accordingly led to a more prominent WSE in the LVF. Cheng and Yang thus argued that the RH plays a more dominant role in Chinese character reading. It is worth mentioning that more studies investigated the hemispheric asymmetry in Chinese character recognition without comparing character against character-like stimuli at the same time. These

studies, using tasks like naming, new-old judgement and semantic category judgement, produced mixed results with regard to whether the two hemispheres are asymmetric in their capability and efficiency of processing Chinese characters (e.g., Kuo, Yeh, Lee, Wu, Chou, Ho, Hung, Tzeng, & Hsieh, 2003; Tang, Xu, & Ou, 1988; Zhang & Peng, 1983). An overview of these different findings will be provided in Chapter 7, which reassesses the effect of visual field on Chinese character recognition and the WSE in Chinese.

## 2.3 Summary

Chapter 1 introduced the research topic of the thesis, the WSE, its contributions to the theoretical understanding of word recognition, its interactions with other well-known effects in word recognition, the Reicher-Wheeler task, and visuoperceptual factors affecting the presence or size of the WSE. The present chapter brings the topic closer to the aim of the thesis (as indicated by the thesis title) by providing a brief introduction to the Chinese language and the state of the art in the WSE research in Chinese.

The introduction to the Chinese language is divided into three parts. Section 2.1.1 firstly clarifies that the terms 'Chinese' and 'Chinese characters' refer to the simplified Chinese and its characters. and then introduces the writing units of Chinese, i.e., stroke, radical, and character. Section 2.1.2 follows by explaining how Chinese characters are different from English words, including their unique two-dimensional compact square shape, inter-radical interactions, varied radical sizing and arbitrary phonology. It also pointed out that an English word does not necessarily map onto a single character in terms of the meaning they carry and the term 'word' in Chinese refers to phrases of two or more characters. This clarification is crucial as some Chinese

researchers entitled their studies as relevant to the WSE in Chinese when they actually meant the superiority of multi-character phrases over meaningless character combinations. The last part, Section 2.1.3, explains how pseudocharacters and noncharacters can be made by violating the radical position regularity.

For the sake of comparisons, the overview of the WSE research in Chinese is organized in a similar way to the structure of Chapter 1. The WSE research in Chinese does not compare to the WSE research in English in terms of the quantity and the depth of published studies. Section 2.2.1 summarizes studies in the existing literature that have specifically investigated the issue and their findings. In contrast to that fact that a robust WSE has been consistently reported in English word recognition studies regardless of tasks, research assessing the WSE in Chinese produced mixed findings. More importantly, several studies used the lexical decision task and reported the noncharacter superiority over pseudocharacters and even characters, which reinforces the point made in Section 1.4 that participants may make the lexical-or-nonlexical decision without seeing or even making the effort to see detailed visual contents. Section 2.2.2 focuses on whether the WSE has been studied in relation to other well-known effects in the broader area of word recognition. Specifically, although most studies using the lexical decision and the naming tasks reported greater performance for high-frequency than for low-frequency characters, Cheng (1981) used a two-alternative forced choice task and observed the opposite pattern which accordingly led to a reduced WSE for high-frequency characters. The Word Length Effect does not apply to character reading due to its square-shaped compactness. As for the Orthographic Neighbourhood Size Effect, the existing literature has used the naming task with no pseudocharacters or noncharacters involved and therefore was unable to determine whether it interacts with the WSE in Chinese.

The WSE research in Chinese does not compare to the WSE research in English also in terms of task stringency and the spectrum of visuoperceptual factors that have been studied in association with the WSE. Section 2.2.3 points out that none of the existing studies has used the Reicher-Wheeler task to properly assess the WSE in Chinese; besides, it also explains the ways in which the two-alternative forced choice paradigm used in previous studies was less stringent than the Reicher-Wheeler task. Section 2.2.4 points out that visual field of presentation is the only visuoperceptual factor that has been examined in relation to the WSE in Chinese with a LVF advantage than the RVF leading to a more prominent character superiority in the LVF.

As emphasized back in Section 1.4, the Reicher-Wheeler task is methodologically more stringent and more appropriate to study visual word recognition than many other tasks. For example, compared to the lexical decision task and the naming task, the Reicher-Wheeler task has the advantage of providing a passive view scenario that is more similar to everyday reading conditions; besides, correct responses in the lexical decision task can be achieved by guess work based on orthographic knowledge without actually seeing or even making the effort to see the detailed visual contents and using the naming task to assess the hemispheric asymmetries in visual word recognition may bias the LH which is known for its dominance in phonological processing. These all highlight the need to re-assess the existence of the WSE in Chinese character recognition, in central and lateralized display, with the proper Reicher-Wheeler task. However, before moving on to these research issues at the centre of the thesis, the next chapter will report an experiment aiming at establishing the optimal retinal image size in normal Chinese reading, which is fundamental to any studies investigating Chinese character recognition and Chinese reading in general yet has never been researched before.

## **Chapter 3. Determining the optimal retinal image size in normal Chinese reading-Experiment 1**

### **3.1 Introduction**

The importance of presenting stimuli at an appropriate retinal image size has long been acknowledged in word recognition and reading research using English. As early as the 1970s (e.g., Eriksen & Eriksen, 1974; Eriksen & Hoffman, 1972, 1973), studies investigated how slight variations in the visual angle occupied by adjacent letters may influence the way in which these stimuli are processed. The empirical evidence from these studies suggests that reading performance benefits when approximately four letters are brought within 1 degree of visual angle, and this agrees with natural reading behaviour (Jordan & Martin, 1987; Rayner & Pollatsek, 1989).

Retinal image size also significantly affects reading performance in at least two important ways. First, retinal image size will affect the spatial frequency content available to the reader and this can have a considerable impact on reading performance. For example, using English text, Legge, Rubin, Pelli & Schleske (1985) pointed out that reduced spatial frequency content can cause loss of visual information and thus impair performance on visual tasks (see also Majaj, Liang, Martelli, Berger & Pelli, 2003; Majaj, Pelli, Kurshan & Palomares, 2002). More recently, Patching and Jordan (2005) found that identification accuracy for English words was different for band-pass filtered words centred at various different frequencies between 1.1 and 13.7 cycles per degree (cpd). Second, unusual retinal image size may interfere with normal patterns of eye movements. For example, studies of eye movements when reading English text found that the lengths of forward saccades (in characters) were effectively shorter when the retinal image size was increased to 5 times the size of normal text (Courier 10 pt) and

above (Mohammed & Dickinson, 2000).

In a similar vein, determining an appropriate retinal image size for character presentation is highly important for research into Chinese character recognition and Chinese reading. However, very few studies have addressed the issue. Huang et al. (2004) examined the effect of retinal image size within the range of 2-19 degrees and concluded that the optimal visual angle for Chinese character recognition lies between 10 and 11 degrees. However, the 2-19 degree range was chosen arbitrarily by Huang et al. and only seven visual angles were examined within the range. The arbitrary choice of unusually large visual angles took no consideration of character size in normal reading. In fact, it would require a viewing distance of  $\sim 1.76$  cm for characters in standard reading material (0.3 cm wide) to subtend a visual angle of 10 degrees. Another study which investigated stimulus size in Chinese reading is Chi, Cai and You (2003) which reported that the minimum visual angle required to identify a Chinese character with a exposure duration of 750 ms was 0.34 degrees. However, the focus of this study was the threshold for recognition and so provides no indication of the optimal retinal image size in normal Chinese reading.

There are two approaches to determining the optimal retinal image size in normal Chinese reading. One approach is to have participants read Chinese text in varied font sizes from a fixed viewing distance and the other approach is by manipulating the viewing distance from which text of a constant font size is read. The first approach requires prior knowledge of a suitable viewing distance for stimulus presentation. Research using alphabetic languages has shown the normal reading distance for a standard typeface is usually between 30.5 and 40.6 cm, with a mean of 35.5 mm (e.g., Sanders & McCormick, 1992). Besides, Legge and colleagues in the 'Psychophysics of reading' series used 40cm as a viewing distance for studying normal

reading behaviour (e.g., Legge, et al., 1985; Legge, et al., 1985; Legge, et al., 1987; Legge, et al., 1989; Mansfield, et al., 1996, Harland, et al., 1998; Chung, et al., 1998). In contrast, over the years, researchers have made arbitrary decisions about the size of Chinese stimuli used in experiments and the viewing distance at which these stimuli were presented. These decisions have resulted in the use of a wide range of viewing distances, ranging from 30 to 200 cm (see Table 3.1). Therefore, compared to manipulating text font size from an arbitrarily chosen viewing distance, it is more feasible and plausible to take the distance approach, namely establishing the optimal retinal image size in normal Chinese reading by systematically varying the distance at which text was presented. This approach was also more ecologically natural in that it mimicked how in real life readers hold reading material in hand and adjust viewing distance for best results.

Accordingly, the purpose of the present study was to assess the effects of viewing distance at which passages of normal, standard size Chinese text were read and thus help establish the optimal retinal image size for normal Chinese text presentation. A widely adopted, standard Chinese typeface (Song, 10.5 pt) was used and an extensive range of viewing distances was selected, with extremes designed to provide a range of reading performances and small intervals to enable a sensitive assessment of the effects of changing distance on reading performance within these extremes. Specifically, the experiment used 40 viewing distances between 2.5 and 100 cm, each neighbouring distance differing by 2.5 cm. Effects of viewing distance were assessed by recording the rate at which passages were read at each distance. The predictions were straightforward. If viewing distance has an effect on Chinese reading, different reading rates should be observed at different viewing distances. Indeed, if Chinese reading is highly sensitive to viewing distance, even small changes in distance should affect reading performance.

	Viewing distance (cm)	Stimulus width (cm)	Visual angle (Degrees)
Hoosain & Shiu, 1989	100	NR (0.7)	0.4
Chan & Lee, 2005	45	0.35;0.5	0.45;0.63
Hsiao et al., 2005, 2006	92	1	0.62
Yeh & Li, 2002	115	NR (1.4)	0.69
Tsai et al., 2004	70	NR (1.1)	0.9
Inhoff & Liu, 1998; Liu et al., 2002	65	NR (1)	0.9
Zhang & Peng, 1983	35	NR (0.6)	1
Perfetti & Zhang, 1991,1995	30	NR (0.52)	1
Lee et al., 2006	60	NR (1.05)	1
Hsiao et al., 2007	100	1.8	1.03
Tan & Perfetti, 1997	50	0.9	NR (1.03)
Chen & Tang, 1998	60	NR (1.3)	1.2
Yeh & Li, 2004	55	NR (1.15)	1.2
Tan & Perfetti, 1999	50	1.05	1.2
Yan et al., 2006	75	NR (1.6)	1.22
Coney, 1998	45	1	NR (1.27)
Fang, 2003	NR	NR	1.3
Tan et al., 1995	150	NR (3.5)	1.34
Valdes-Sosa et al., 1993	80	4	1.43
Bai & Shen, 1995	165	4.2	1.46
Zhang et al., 2004	NR	NR	1.5
Shimoyama et al., 1997	200	NR (5.6)	1.6
Kuo et al., 2001	194	NR (6.8-10.1)	2-3
Kuo et al., 2003,2004; Lee et al., 2004	194	NR (7.8)	2.3

Hinojosa et al., 2000	65	NR (3.4)	3
Dong et al., 2005	NR	NR	3±1
Tse et al., 2000	57	NR (4)	4
Huang et al., 2004	50	NR (8.8-9.7)	10-11 (concluded as optimal)
Lin & Shieh, 2006	55	NR	NR

Table 3.1 Viewing distances, stimulus widths, and visual angles reported in the literature. NR stands for 'Not Reported' and parenthesized figures are estimates based on the two other parameters if provided in the original study.

## 3.2 Methodology

### 3.2.1 Participants

Twenty participants (aged 21-26) took part in a single session. All were native speakers of Chinese, reported normal or corrected to normal vision, and were screened using a Bailey-Lovie eye chart (Bailey & Lovie, 1976) for minimum binocular acuity of 3/3 or better.

### 3.2.2 Stimuli

Forty-two passages of text were selected from stories published in the most recent issues of Globe Times, a popular Chinese daily newspaper. Passages were all travelling notes describing interesting stories and experiences outside China and provided an engaging text. Each passage contained approximately 648 Chinese characters in 4 paragraphs and was presented in its entirety in a single screen display. All passages had their starting character in the same position in the top-left corner of the screen.

### 3.2.3 Visual conditions

Each passage of text was shown as it would appear in normal printed Chinese format. Song is used as a common, standard typeface in mainland China, and for many years it has been the default typeface for simplified Chinese in Windows and Microsoft Office products (also known as SimSun). Formal Chinese publications like books and newspapers use Song presented at 10.5 pt as the standard font size for text (Zhu, Li, Wu & Zhu, 2005). Therefore, these two parameters were employed in the current study to reproduce the typical layout of printed Chinese texts so that each single character occupied approximately 0.30 cm (horizontally and vertically), 28 characters were shown in each line (allowing for punctuation), and inter-line spacing was 0.25 cm. All characters were presented in black on a white background. Background luminance was 99cd/m<sup>2</sup> and stimulus luminance was 6cd/m<sup>2</sup>. Each text occupied a screen area measuring approximately 10.5 cm horizontally and 15.0 cm vertically.

### 3.2.4 Apparatus

All passages were presented on a Samsung SyncMaster 753s monitor set to a resolution of 1280 x 1024. A Cambridge Research Systems VSG 2/5 card was used to control stimulus presentations and record reaction times via a Cambridge Research Systems CT3 response box. Participants remained seated in a constant location and the location of the monitor was adjusted appropriately for each viewing distance used in the experiment. Participants were seated in a normally illuminated room and a chin-rest was used to ensure accurate viewing distance throughout the experiment.

### 3.2.5 Design and procedure

Forty-two passages were used in the experiment. Two passages were designed to be used as practice stimuli and the remaining 40 passages were used as experimental stimuli. Each participant was shown a different experimental passage at each of forty

distances within the range of 2.5 to 100 cm, inclusive. The order in which distances were used was counterbalanced across participants using a Latin Square design.

For each trial, the monitor was adjusted to the appropriate viewing distance (along the 2.5-100.0 cm continuum). Each trial started with a fixation dot in the top-left corner of a blank screen, denoting where the initial character of the passage would appear. Participants were instructed to fixate the dot and to press a button on the response box when they were ready to read the passage. This button press initiated the presentation of the passage and started the timer. Participants read each passage of text through once, silently, from top left to bottom right, as they would normally when reading Chinese text. After reading the final character of each passage, participants pressed the button again. This immediately removed the passage from the screen and stopped the timer. Prior to the presentation of the experimental passages, participants were given 2 practice passages to familiarize themselves with the experimental procedure and the appearance of the text. To ensure that passages were read for meaning, five questions were asked after each passage, each addressing a key point in that passage. The criterion of a minimum of 60% correct was used for each set of five questions to ensure participants were reading sufficiently carefully to comprehend the passage. All 20 participants matched or exceeded this accuracy criterion for every passage. Mean accuracy for each of the 40 distances was above 90%.

### 3.3 Results

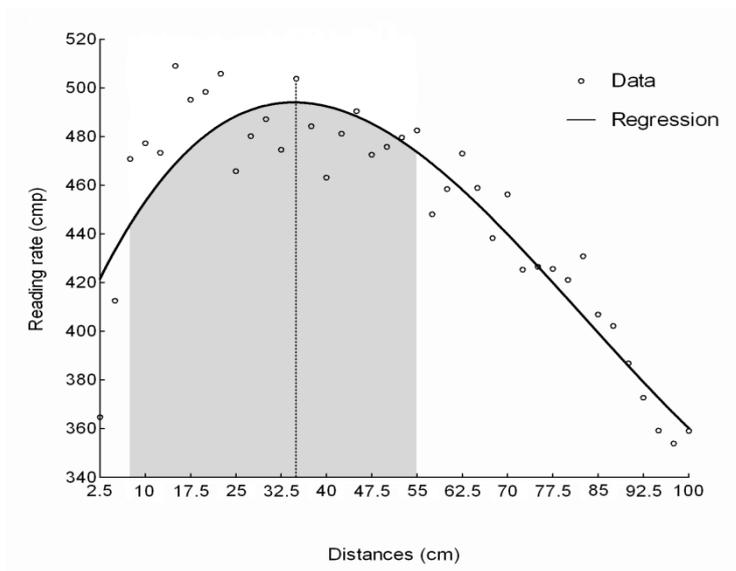


Figure 3.1. Mean reading rates at the 40 distances used in the experiment and the regression curve of the means. The grayed-out area corresponds to the critical range 7.5-55.0 cm under the regression curve. Any mean reading rate within this area (range mean = 477 cpm) is significantly faster than that at 2.5 cm and at 92.5-100.0 cm (range mean = 358 cpm). The dotted line shows the maximum mean reading rate on the curve of 494 cpm at approximately 35 cm.

Reading rate was defined as the number of characters read per minute. Mean reading rates for the forty viewing distances are shown in Figure 3.1. A one-way ANOVA, with Greenhouse-Geisser correction to provide a more conservative analysis, showed a main effect of distance,  $F(9.30, 176.65) = 6.96, p < .001, \eta_p^2 = .27$ . Bonferroni post-hoc t-tests were conducted between all pairs of distances and revealed a pattern of performance that is best described as 6 ranges, namely, 2.5 cm, 5.0 cm, 7.5-55.0 cm, 57.5-70.0 cm, 72.5-90.0 cm, and 92.5-100.0 cm. The main findings across these different ranges are as follows.

1. Reading rate did not differ significantly across distances within the same range.
2. Reading rate at 2.5cm did not differ from reading rates at any distance within

the range 92.5-100.0 cm.

3. Reading rate at 5 cm did not differ from reading rates at either 2.5 cm or within the range 92.5-100.0 cm.

4. Reading rates within the range 7.5-55.0 cm were faster than at 2.5 cm and at any distance within the range 92.5-100.0 cm (all  $p$ s < .05).

5. Reading rates within the range 57.5-70.0 cm showed evidence of decreasing towards the levels of performance observed at the extremities (2.5 and 92.5-100.0 cm). In particular, performance at 57.5 cm, 67.5 cm and 70.0 cm did not differ from performances at 2.5 cm or at any distance within the range 92.5-100.0 cm.

6. Reading rates within the range 72.5-90.0 cm did not differ from reading rates at either 2.5 cm or at any distance within the range 92.5-100.0 cm.

Following these analyses, a cubic model (third order polynomial) was fit to the data (see Figure 3.1). The model revealed that a maximum mean reading rate of 494 characters per minute (cpm) occurred at approximately 35.0 cm, corresponding to an optimal (horizontal) visual angle for each character of 0.5 deg.

### 3.4 Discussion

The purpose of this study was to assess the effects of viewing distance at which passages of normal, standard size Chinese text were read and thus help establish the optimal range of retinal image sizes for experiments investigating normal Chinese character reading. The motivation for this research was heightened by the large variety of viewing distances and stimulus sizes used previously in the literature to study Chinese character reading. To provide a precise assessment of the effects of viewing distance, an extensive range of viewing distances was used, with extremes designed to

produce a range of reading performances with a common standard font and small intervals within these extremes to enable a sensitive assessment of the effects of changing distance on reading performance. The results revealed a pattern of performance that is best described as 6 ranges, and we defined the optimal range as a continuous range within which each single distance produced faster reading rate than that at extreme distances used in the study (2.5cm; 92.5-100.0 cm). Therefore, our findings indicate that 7.5-55.0 cm is the optimal viewing distance range (mean reading rate = 477 cpm) for normal Chinese reading, and regression analysis suggested a maximum mean reading rate of 494 cpm at approximately 35.0 cm, corresponding to a retinal character size of 0.5 degrees.

These findings offer a number of insights into the processes underlying efficient Chinese reading. First, 7.5-55.0 cm is a range in which certain key spatial frequencies may be available. A substantial body of psychophysical evidence indicates that the human visual system operates in the spatial frequency domain, responding to visual patterns on the basis of their spatial frequency content. Sensitivity to various spatial frequencies is known to vary systematically (e.g., Campbell & Robson, 1968; Graham, 1989) and, in general, the human visual system is most sensitive to spatial frequencies in the range of 2-6 cpd, and more contrast is needed for detection of lower and higher spatial frequencies. In line with this research, many investigations have taken place into the role of spatial frequency in reading (at least for English text and letters: Majaj et al., 2003; Majaj et al., 2002; Patching & Jordan, 2005). Legge et al. (1985) found that maximum reading rates are achieved for characters (letters) subtending between 2.0 degrees and 0.3 degrees. Similarly, in our experiment, characters in a typical Chinese typeface (Song, 10.5 pt) presented within the optimal range 7.5-55.0 cm subtended between 2.3 degrees and 0.3 degrees which resembles the Legge et al. finding.

Moreover, within this optimal range, spatial frequencies corresponding to overall character width were between approximately 0.2 and 1.6 cpd and these are low spatial frequencies to which the magnocellular pathway is most sensitive (Legge, 1978; Merigan, Byrne, & Maunsell, 1991; Skottun, 2000); and spatial frequencies corresponding to stroke width were between approximately 2.2 and 16.1 cpd. Consequently, the optimal reading performance observed within this distance range suggests that visual information extracted within a range of 3.3-octave spatial frequency bands with centre frequencies of between 0.7 and 5.1 cpd is particularly useful for reading Chinese characters. Indeed, the indication from the regression analysis is that spatial frequencies of 1 cpd and 10 cpd correspond to overall character width and stroke width, respectively, and so suggests more specifically that these spatial frequencies might be particularly valuable for readers of Chinese. Furthermore, the centre frequency of this band, 3.2 cpd, resembles the peak of the spatial contrast sensitivity function of human vision (Campbell & Robson, 1968), suggesting that this pattern of reading performance has its foundation in the visibility of information in Chinese characters. Nevertheless, the range in viewing distances at which performance was optimal suggests that efficient reading of Chinese text can be achieved using a range of scales of information, and that the use of this information is flexible. However, the impaired performances we observed for distances outside this optimal range indicate the limits of this flexibility.

Second, distances within the optimal distance range of 7.5-55.0 cm may be better suited to producing the eye movement patterns that are essential in everyday Chinese reading. Morrison and Rayner (1981) noted that fixation duration increased slightly as viewing distance increased from 36 to 53 to 71 cm, and they suggested that this is probably due to the fact that characters might be less discriminable at greater

distances, resulting in longer fixations. Thus, the distances above the optimal range in our experiment (especially those of 92.5 cm and above) are likely to have produced substantial difficulty in character discrimination which induced longer fixation durations to compensate, and therefore induced significantly slower reading rate. At the shorter distances in the experiment below the optimal range (2.5 cm and 5 cm), characters subtended larger retinal image sizes with the result that more characters fell in the less sensitive parafovea and peripheral areas of vision, which may have contributed to the impairment in reading performance we observed. In addition, readers experience different aspects of visual fatigue induced by adaptive changes in the resting states of accommodation and convergence in near vision (Owens & Wolf-Kelly, 1987) and so the extremely short viewing distances of 2.5 and 5 cm used in our experiment may have exacerbated this situation. It is interesting to note that the optimal viewing distance of 7.5-55.0 cm we observed in the experiment is also a range in which, given the length of human arms, material can be held comfortably in the hands for reading.

The finding that 7.5-55.0 cm is the optimal distance range in normal Chinese reading suggests that distances within this range are appropriate for normal Chinese text presentation in experiments. However, it should be noted that the optimal viewing distance range we observed was based on using Chinese text stimuli in standard print size (0.3 cm horizontally and vertically). If a display in an experiment does not have a resolution high enough to accurately present Chinese characters in standard print size, the retinal character sizes (2.3-0.3 degrees) corresponding to those distances within the optimal distance range can be achieved by using distances greater than 55.0 cm. Nevertheless, caution should be taken when distances substantially away from the optimal range, especially those of 92.5 cm and above, are considered as the viewing distance in an experiment designed to investigate normal Chinese reading. This is

because perception of Chinese characters at shorter distances is part of natural reading and the processes involved may be disrupted when the viewing distance is very different from that encountered in everyday reading. Indeed, abnormal viewing distances (e.g., 165cm, 194cm and 200 cm, see Table 1) may bring their own confounding influences. As described by Leibowitz (1971), the initiation of oculomotor movements for focusing stimuli is coupled with a subjective expectation that this action will be accompanied by a change in the size of the retinal image. The influence that this expectation has on the perception of size was demonstrated by Leibowitz and Moore (1966), who showed that different viewing distances alter the perceived extent of a stimulus, even though the stimulus in their experiment always occupied the same visual angle (1 degree).

In summary, the present study found that viewing distance has a substantial effect on performance in normal Chinese reading. Better reading performance was observed when characters in a standard typeface and font size were viewed from distances ranging between 7.5 and 55.0 cm. This finding has implications for understanding the processes involved in normal Chinese reading and for presenting Chinese stimuli in experiments designed to study these processes. By presenting stimuli guided by the viewing distances and associated retinal image sizes identified in this study, experiments can reveal more precisely the processes involved in Chinese character reading.

## **Chapter 4. Character and pseudocharacter superiority investigated with inversion of stimulus-Experiment 2**

### 4.1 Introduction

In spite of the importance of the WSE and context effects in English letter and word recognition, the effects of context in Chinese character recognition remain to be fully revealed. Cheng (1981) is the first published study that specifically investigated this very topic and found the character superiority over pseudocharacters and noncharacters. It used a two-alternative forced choice paradigm which sounds seemingly similar to the Reicher-Wheeler task. However, as noted earlier in Section 2.2.3,, it was far less stringent than the Reicher-Wheeler task. One of its major methodological flaws was that the making of pseudocharacters was not systematic in it. For the majority of characters, their pseudocharacter counterparts were formed in the same manner as described in Section 2.1.3, namely, by replacing one of the component radicals in a genuine character with another radical to form a novel combination of radicals (as illustrated in the top two rows, Figure 4.1); whereas for other characters, their pseudocharacter counterparts were made by replacing all component radicals, thus making pseudocharacters completely unrelated to their character counterparts (see the middle two rows, Figure 4.1). This is analogical to using 'vout' as the paired pseudoword for the word 'read' with no shared letters as the basis for comparing letter identification performance in word context against in pseudoword context. Besides, stimuli of different spatial constructs were used across conditions, e.g., top-bottom structured pseudocharacters paired with left-right structured characters (see the middle rows and the bottom row, Figure 4.1). Its methodological design may be further contaminated by failing to counterbalance either the proportions of characters of

different spatial constructs or the proportions of characters with different critical radical positions. Specifically, 21 pairs of left-right structured, 1 top-bottom structured, and 2 half-closed structured, and moreover, for the 21 pairs of left-right structured characters, 12 pairs had the radical on the left as the critical radical, while only 9 had the radical on the right as the critical radical. As a result, neither the critical radicals nor the critical positions were counterbalanced across conditions in the experiment and these can produce confounding and thus prevent a clear assessment of contextual effects in character recognition.

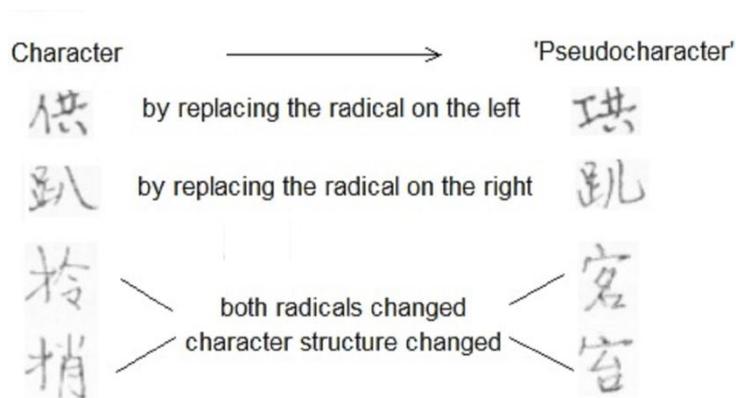


Figure 4.1. An illustration of how pseudocharacter stimuli were created in Cheng (1981). The left-most column shows 4 sample characters from top to bottom and the 'matched pseudocharacter' for each of them was shown in the same row under the right-most column. The information in between explains the relationship between characters and their 'matched pseudocharacters'.

In the decades after Cheng (1981), a few more studies specifically investigated the Word Superiority Effect in Chinese. Mattingly & Xu (1994) adopted a lexical decision task, Mok (2009) used a modified Reicher-Wheeler task, and they both used two-character compound words as stimuli rather than single characters. More recently, Kao, Chen, & Chen (2010) assessed the word superiority effect in Chinese by asking participants to judge whether two bilaterally presented characters were the same or different.

Indeed, although not directly addressing the issue of effects of context in

Chinese character recognition, there exist other studies which included character and pseudocharacter and/or noncharacter conditions (e.g., Chen, Allport & Marshall, 1996; Taft & Zhu, 1997). These studies have used different experimental tasks and produced mixed findings. Chen, Allport & Marshall (1996) used same-different judgement task, which requires participants to decide whether two stimuli shown simultaneously, one above the other, are the same character or not, and reported a character superiority over pseudocharacter and noncharacter as well as a pseudocharacter superiority over noncharacter. However, presenting two stimuli simultaneously on the screen may induce interference from each other (e.g., McClelland & Mozer, 1986), besides, this task has shifted the focus away from lexical activation of a target item itself and participants' performance may reflect more of their comparing efforts under certain attentional mechanism rather than the normal processes in Chinese character recognition. Taft & Zhu (1997) manipulated in a lexical decision task the frequency of the two radicals within left-right structured characters and found a word superiority over pseudocharacters along with a single radical superiority over pseudocharacters. Nevertheless, in a lexical decision task, it is likely that readers can tell the lexical status of a target stimulus without recognizing it. This is because presenting letters against spelling rules has been the conventional way to form nonwords, and once any piece of information in a nonword stimulus is spotted against spelling rules participants can make the decision without processing the remaining part of the stimulus. For example, in the nonword `orwk', even if participants only saw `rw' or `wk' in it, a decision could be made without the necessity of activating the rest of the stimulus as either of them is acceptable. Besides, lexical decision task also suffers the problem of involving other post-access cognitive processing like reasoning.

The purpose of Experiment 2, therefore, was to provide clearer assessment of

the role of context (within which radicals are perceived) by following the stringency of the Reicher-Wheeler task and overcoming the confounding factors in previous studies. Specifically, left-right structured compound characters were used in the character condition as they are most frequent in the whole Chinese vocabulary and will certainly also make production of matched pseudocharacter stimuli more feasible compared to those less common character structures like top-bottom and closure structures. Carefully matched pairs of characters and pseudocharacters ensured both critical radicals and critical positions counterbalanced across conditions. Two more stimulus types were included in this study as control conditions, the inverted characters (characters vertically flipped over) and the visual matches to characters (hereafter will be referred to as VMs). The VM stimuli were generated individually for each character by breaking strokes into fragments and then repositioning these stroke fragments within either radical so that all original strokes were destructed whereas the overall contour of both radicals and consequently of the entire character was more or less maintained. As a result, both the inverted condition and the VM condition contained the same amount of visual contents (in terms of overall pixel number) as in the character condition while depriving the visual contents of their lexical context.

These experimental conditions were carefully designed to examine the role of context, the WSE in particular, in Chinese character recognition. Hypothesis for identification performance in each of the four conditions is as follows. Visual information in characters were most degraded in the VM stimuli and therefore would be most difficult to extract and utilize which should result in the poorest identification performance of participants. If there exists top-down benefits from the lexical context in Chinese character perception, a character superiority should be observed over all other conditions where these benefits were not available. However, if there exists certain

orthographic mechanism underlying pseudocharacter processing and if this orthographic mechanism is as efficient as the lexical mechanism in radical reading, participants will be equally accurate when identifying a critical radical in both character and pseudocharacter contexts.

## 4.2 Methodology

### 4.2.1 Participants.

Eighteen participants (aged 19-26) took part in three sessions. All were native speakers of Chinese, reported normal or corrected to normal vision, and were screened using a Bailey-Lovie eye chart (Bailey & Lovie, 1976) for minimum binocular acuity of 3/3 or better.

### 4.2.2 Stimuli

Fifty matched sets of left-right structured character and pseudocharacter stimuli were prepared, each set consisting two pairs of characters and two pairs of pseudocharacters. The members of each pair differed by just one 'critical' radical. The critical radicals occurred equally often at either of the two radical positions (left or right), which means twenty-five sets of character and pseudocharacter stimuli had the critical radicals on the left and the other twenty-five sets on the right. Within each set, the critical radicals and the non-critical radicals were also counterbalanced across conditions to avoid the confounding factor that any difference in performance when choosing between two critical radicals could either be due to the stimulus condition or the identity of those particular critical radicals or the identity of their accompanying non-critical radicals. Detailed manipulation is exemplified in Figure 4.2 (see Appendices 1 and 2 for more stimuli). Fifty matched sets as exemplified in Figure 4.2 led to 200 characters and 200 pseudocharacters. Based on the 200 characters, 200

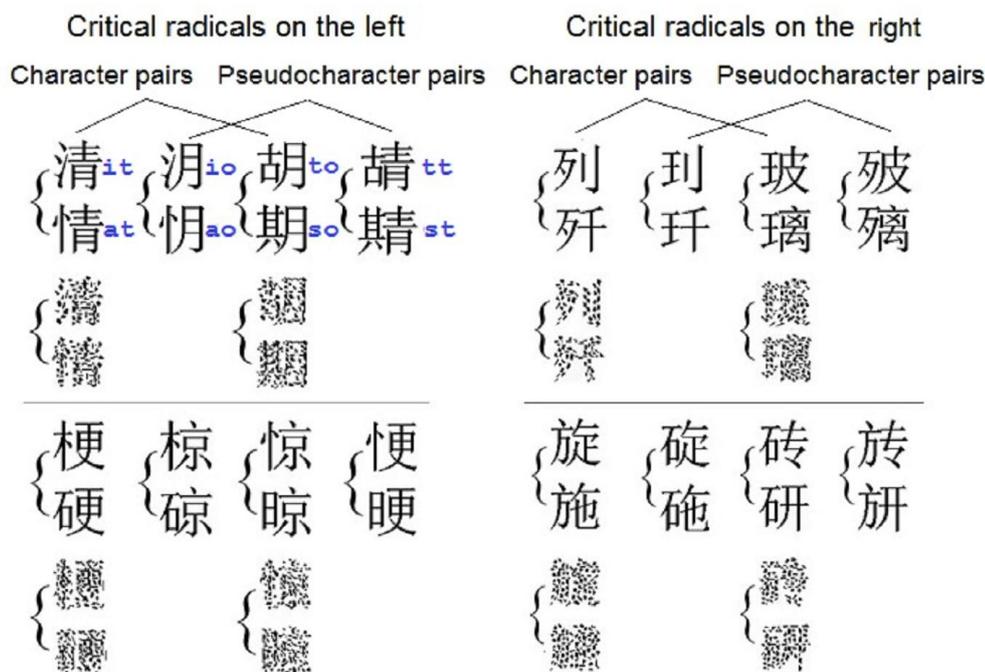


Figure 4.2. Examples of characters and their matched pseudocharacters and VMs. Two sets, divided by a horizontal line, of matched pairs of characters, pseudocharacters and VMs are shown on either the left or the right side. On the left side, the two alternative choices within each pair of stimuli differed by the radical on the left; and the other way around on the right side. Take the first set of matched stimuli in the top-left quarter for example. The first pair of stimuli contains two characters which differ by the radical on the left (critical radicals). To create pseudocharacter context for discriminating between these two critical radicals, the radical on the right (shared, non-critical radical) in either character was replaced by another radical which can occur in this position, resulting in a novel combination of radicals and accordingly a pair of pseudocharacters. Then the critical radicals in this matched pair of pseudocharacters were replaced by another pair of critical radicals to make a second pair of characters. Finally, the new pair of critical radicals combined with the non-critical radicals in the first pair of characters to make a second pair of pseudocharacters. The 2-letter strings are provided to help understanding the careful manipulation, which ensured that the identities of critical and non-critical radicals were counterbalanced across conditions. The position of critical and non-critical radicals was counterbalanced in the sample stimuli shown on the right of the figure.

inverted characters and 200 VMs were then prepared in the method explained earlier in the Introduction to this chapter. An additional 96 pairs of stimuli under each of the four stimulus conditions were constructed to provide 32 practice items at the beginning of each session. Both items within each matched pair were shown as target stimuli.

### 4.2.3 Visual conditions.

As in the previous experiment, Song was used as the typeface for the construction of stimuli, which were presented in black on a white background. Background luminance was 99cd/m<sup>2</sup> and stimulus luminance was 6cd/m<sup>2</sup>.

Chapter 2 introduced several distinctive features of Chinese writing including the squared compactness of characters, the size variation of radicals, and the radical interactions in characters. Unlike English letters which are similar in their width except a few being slightly thinner or wider than average (i.e., i, l, m, w), Chinese radicals show more dramatic width differences. More importantly, not only different radicals have different widths, even the same radical may show width variations in different characters. It was also noted in Chapter 2 that character stimuli used from this experiment on were all left-right structured SP/PS characters which are typically combinations of a thinner radical (semantic) and a wider radical (phonetic). For a particular character stimulus, its pseudocharacter counterpart was made by replacing a radical in the word with another radical to form a non-existing combination. If the two component radicals in a pseudocharacter were both thin or both wide, the pseudocharacter as a whole would also be considerably thinner or wider than a character. If a pseudocharacter contained two thin radicals, one way to achieve the square-ness feature of characters was to simply keep the two component radicals apart for as much distance as needed. However, this would lead to the violation of the radical interactive-ness feature of characters and the result would look nothing like an integrated whole but a 'radical-space-radical' sequence (refer back to Section 2.1.2 for details). If a pseudocharacter contained two wide radicals, the square-ness feature of characters would be violated and it was simply impossible for this 'made-up' combination to look character-like as an integrated whole without modifying the width of one or both

radicals. Therefore, radical size alterations were called for when needed in order for pseudocharacter to appear more natural and character-like. As illustrated in Figure 4.2, within each set of two matched pairs of characters and two matched pair of pseudocharacters, the critical radicals (by which the two alternatives in a matched pair of characters or pseudocharacters differed) and the non-critical radicals (which the two alternatives in a matched pair of characters or pseudocharacters shared in common) were counterbalanced across conditions, which means that each radical occurred once in the character condition and once in the pseudocharacter condition in exactly the same size. There were two consequences of the radical resizing and the radical counterbalancing. On the one hand, since radical size alteration was performed case by case, characters and pseudocharacters did not have a constant width. Specifically, viewed from 35cm, characters (and accordingly inverted characters and VMs) and pseudocharacters subtended horizontal visual angles between 0.3 and 0.76 degrees, with a mean of approximately 0.5 degrees, which corresponded with the optimal retinal image size for normal Chinese reading established in the previous chapter. On the other hand, radical counterbalancing across stimulus conditions ensured equal overall width of stimuli across conditions. In other words, although individual characters (accordingly inverted characters and VMs as well) and pseudocharacters, may have varied widths, the overall width of all items under different conditions was the same and any differences in participants' responses between conditions could not be due to that the width of one condition was thinner or wider than another.

#### 4.2.4 Apparatus

Apparatus was the same as used in Experiment 1. stimuli were presented on a Samsung SyncMaster 753s monitor set to a resolution of 1280 x 1024. A Cambridge Research Systems VSG 2/5 card was used to control stimulus presentations and record

reaction times via a Cambridge Research Systems CT3 response box. Participants were seated in a darkened booth and a chin-rest was used to ensure accurate viewing distance throughout the experiment.

#### 4.2.5 Design

A blocked randomization design was used in this study. There were four stimulus conditions, namely, characters, pseudocharacters, VMs, and inverted characters, which made the four levels of the within-subject factor. There were 200 items under each experimental condition which were randomized and broken down into 3 lists (containing 66, 66, and 68 items, respectively). Lists were then grouped together to form 3 blocks of test items, each containing equal number of test items across conditions. Specifically, two blocks contained 66 items from each of the four stimulus conditions and the other block contained 68 items from each stimulus condition. Items within each block was quasi-randomized for each participant with the constraint that no more than 4 target stimuli of the same stimulus condition were shown in succession. In addition, the order in which these 3 blocks were presented was counterbalanced across participants. Response error rate were taken as dependent measures.

#### 4.2.6 Procedure

The experiment procedure on each trial along the time line is shown in Figure 4.3. At the start of each trial, a small fixation point appeared at the centre of the screen. As the present experiment aimed to investigate the recognition of centrally displayed Chinese characters for which precise fixation is not as critical as for when investigating visual recognition outside of the fovea, participants were only instructed orally and in writing to look at the central fixation point before initiating a target display. When participants pressed either the top or the bottom button on the response box, the fixation point was immediately replaced by a target stimulus in the centre of the screen. The

stimulus exposure durations employed in the majority of Reicher-Wheeler studies using letter strings as stimuli were typically between 30-100 ms (e.g., Carr et al., 1978; Coch & Mitra, 2010; Jordan, Patching, & Milner, 2000; Martin, Nasir, Thierry, Paulignan, & Démonet, 2006; Martin, Thierry, Démonet, Roberts, & Nazir, 2007; Reicher, 1969; Rumelhart & McClelland, 1982; Samuel et al., 1982). In contrast, Chinese readers seem capable of achieving efficient character recognition with shorter stimulus exposure durations. Cheng and Yang (1989), in particular, individually determined a stimulus exposure duration for each participant to ensure 75% correct of a set of practice trials and obtained a mean stimulus exposure duration of 12.43 ms across participants. The flexibility of adjusting stimulus exposure durations in the present study was constrained by hardware limitations. The stimulus exposure time nearest to 12.43 ms that the stimulus presentation monitor could produce was 17 ms (one frame), which was therefore used as target exposure time in the present and the subsequent experiments. Recall that when the WSE was first introduced at the beginning of the thesis, it was mentioned that it is often associated with backward pattern masking, which will be elaborated on in the following chapter. However, in Cheng (1981) and Cheng and Yang (1989) where a two-alternative forced choice task was employed (refer back to Section 2.2.3 and the introduction of the present chapter for how it differed from the Reicher-Wheeler task), the WSE of characters was obtained without using masking. Therefore, the present experiment, as the first move in a series of attempts to re-examine the WSE in Chinese, would be conducted without masking. After target stimulus presentation, two alternative choices immediately followed, one above the other in the centre of the screen, and remained in their positions until participants made a choice by pressing the top or the bottom button to indicate that the top or the bottom item was the target stimulus that they had just been shown. There were 32 practice trials at the beginning of

each block. Each block last approximately 8 minutes and participants took a 5-min break between blocks.

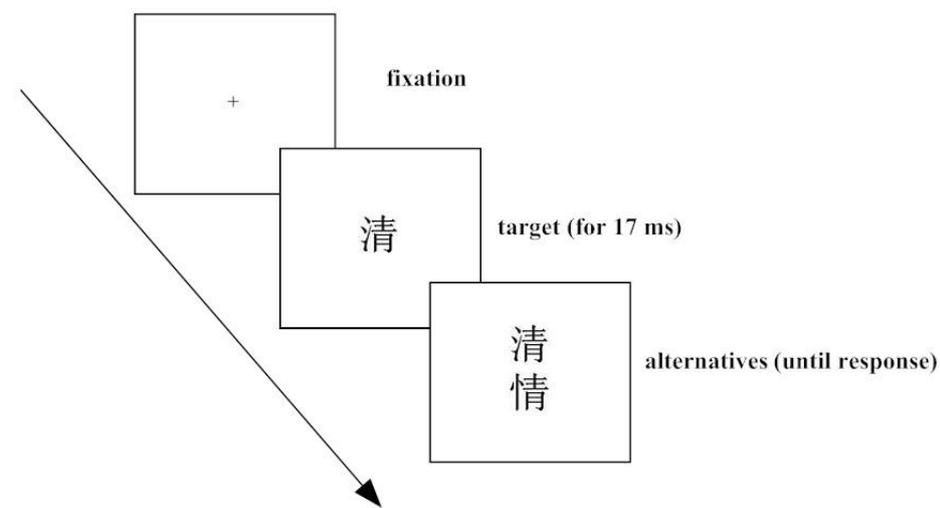


Figure 4.3. Trial procedure of Experiment 2 along the time line.

### 4.3 Results

Mean identification error rate for each of the 4 experimental conditions is shown in Figure 4.4. One-way Repeated measure ANOVA showed a strong main effect of stimulus type ( $F(3,17) = 65.71, p < .001, \eta_{\{p\}}^2 = .81$ ). Post-hoc t-tests revealed that identification performance was most accurate for characters (22% mean error rate) and pseudocharacters (24%) while not differing from each other, less accurate for inverted character (34%) and highest percentage of errors were made in response to VMs (40%).

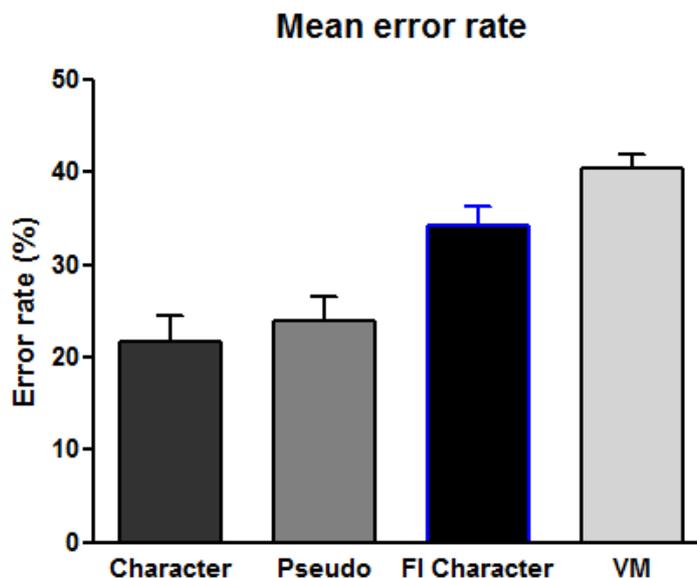


Figure 4.4. Mean error rate across experimental conditions. 'FI' stands for 'fully-inverted' and 'VM' for 'visual match of character'. Bars depict standard errors.

## 4.4 Discussion

The results of Experiment 2 clearly show that the context in which the visual components of a character are presented significantly affects how these contents are perceived by Chinese readers. Specifically, two types of superiority effects were observed, namely, the character superiority and the pseudocharacter superiority over inverted characters and VMs. In addition, an advantage in terms of response accuracy was also found for inverted characters compared to VMs.

The phenomenon that identification performance is better for upright than for inverted stimuli is typically referred to as the inversion effect, which has been shown in a substantial number of studies by using various categories of stimuli. In addition to words, faces and human postures are among the most discussed categories of stimuli that can produce the inversion effect (e.g., Curby & Gauthier, 2009; Leder & Bruce, 2000; Reed, Stone, Grubb, & Mcgoldrick, 2006). More importantly, even stimuli that are only familiar to certain groups of observers have also been associated with the

inversion effect when they were presented to those groups of observers, for example, presenting upright and inverted images of dogs to dog experts, images of cars to car experts, or images of novel objects to well-trained observers (e.g., Diamond & Carey, 1986; Curby, Glazek, & Gauthier, 2009; Gauthier & Tarr, 1997). The inversion effect is commonly taken as evidence that visual processing may be altered by perceptual expertise. More specifically, as Tanaka and Farah (1993) commented, when performing a well-practiced visual task, the visual system tends to employ a holistic approach by focusing more on the structural or spatial relationship among the features of the viewed objects than on the features themselves.

The finding of character advantage over inverted characters in the present experiment (12% accuracy difference) is similar to the finding of Kao, Chen and Chen (2010) in which an inversion effect of approximately 15% accuracy difference was observed. This may readily be taken as evidence of holistic visual processing of characters if there had been no pseudocharacter advantage over inverted characters at the same time. Pseudocharacters were combinations of legal radicals in their illegal positions and accordingly were deprived of familiar overall outline and familiar inter-radical interactions which are exclusive to characters. Therefore, pseudocharacters can be considered as upright radicals in an unfamiliar context and inverted characters as the same radicals put upside down in an unfamiliar context. The pseudocharacter advantage over inverted characters in the present study suggests that radicals can be processed as a whole when not in a character context. The holistic visual processing of radicals emphasizes information like stroke orientation and spatial interactions between strokes rather than individual strokes. It is believed that the distortion of supra-stroke information in the inverted character condition led to the impaired identification performance. However, the finding of both character and pseudocharacter advantage

over inverted characters without character advantage over pseudocharacters brings the confounding that the character advantage over inverted characters may have been the consequence of inversion effect on the whole character basis or on the individual radical basis. To be more specific, one of the possible explanations for the absence of character superiority over pseudocharacters is that the familiar coarse-scale configurational information in characters plays no facilitatory role in character recognition and activation at the character level provides no significant beneficial feedback towards the radical level. If this hypothesis was true, characters and pseudocharacters can be both thought of as combination of an upright radical and another upright radical while the combination being legal or illegal makes no significant difference. Therefore, when compared against inverted characters which contained an inverted radical accompanied with another inverted radical, the character and pseudocharacter advantage over inverted characters may both reflect the inversion effect on the radical basis.

As for the advantage of inverted characters over the VMs, it might be explained by two factors. Firstly, strokes, the bottom level of the Chinese orthographic structure, were intact themselves in inverted characters except for in different orientations; in contrast, these fine visual elements were destructed into random fragments composed of meaningless pixels in VMs. Secondly, although inversion completely changed the 'absolute' orientational properties of strokes and radicals in a character, their 'relative' spatial relationships were kept to some extent, which might still provide useful information in discriminating between the two alternative choices.

The present study failed to obtain significant character superiority over pseudocharacters. This may indicate that radicals are processed independent of its context and the configurational information beyond the radical level in characters plays no facilitatory role in its identification. However, although not statistically significant,

there was a numerical tendency of increased error rate for pseudocharacters compared to characters. This makes another explanation possible. Specifically, when a radical was perceived in a pseudocharacter context, the interaction between this radical and the other radical in this 'made-up' combination and the overall outline of this 'made-up' combination were all novel to participants and may have a negative impact on the identification of the radical (refer back to Section 2.1.2 for details of the radical interactive-ness feature of characters); however, this inferiority effect failed to show through due to certain aspects of the experiment setting. Indeed, many studies have shown that the word superiority effect is more prominent in more severely data-limited viewing conditions including reduced exposure duration, masking, and degraded stimulus quality (e.g., Stanners, Jastrzembski, & Westbrook, 1975). However, not only was it impossible to decrease stimulus exposure duration due to hardware constraints but also an average identification accuracy of around 75% was achieved across stimulus conditions with 17 ms stimulus exposure duration. This motivated the next experiment which would use visual masks to limit visual access.

## **Chapter 5. Character superiority over pseudocharacters investigated with backward masking-Experiment 3**

### 5.1 Introduction

Findings of the previous experiment clearly shows that the context in which the visual components of a character are presented significantly affects how these contents are perceived by Chinese readers. Specifically, two types of superiority effects were observed, the character superiority and the pseudocharacter superiority over inverted characters and VMs. The character and pseudocharacter superiority over inverted characters may be taken as manifestation of the inversion effect, which has been associated with English words and items of other categories. The inversion effect is generally believed to reflect holistic visual processing of items that are familiar to observers, with spatial configurational information playing a critical role. Considering that pseudocharacters are upright radicals in a nonlexical context whereas inverted characters are the same radicals inverted in a nonlexical context, the pseudocharacter advantage over inverted characters indicates that radicals are processed as a whole when not in a character context. The holistic visual processing of radicals emphasizes information like overall radical outline, stroke orientation and spatial interactions between strokes, which was maintained in pseudocharacters yet distorted in inverted characters and thus led to poorer identification performance under the inverted condition. However, without the WSE for characters over pseudocharacters, the nature of the character superiority over inverted characters is ambiguous in that it is difficult to determine whether it was due to inversion effect on the character basis or on the individual radical basis.

One possible explanation for the absence of character superiority over

pseudocharacters is that radicals are processed the same way regardless of the character context. That is, configurational information beyond the radical level in characters plays no facilitatory role in its identification. However, given that there was a numerical tendency of increased error rate for pseudocharacters compared to characters, it is more likely that it reflects a facilitatory effect of familiar configurational information on character perception, which for some reason failed to reach statistical significance. Indeed, many studies have shown that (e.g., Stanners, Jastrzembski, & Westbrook, 1975). The absence of significant WSE for character over pseudocharacters in the previous experiment may suggest that the experiment setting allowed Chinese readers to extract sufficient amount of useful information in pseudocharacters within 17 ms to achieve similar level of identification accuracy as for characters.

Among the various ways mentioned above to increase the visual difficulty of the task, reducing stimulus exposure duration and using masking can both fulfill the requirement while maintaining the natural appearance of characters as they would be encountered in everyday reading. Due to limitations of the hardware (monitor of 60Hz frame refresh rate), it was not possible to reduce the stimulus exposure duration to below 17 ms. More importantly, an average identification accuracy of around 75% across stimulus conditions in Experiment 2 showed that 17 ms was an appropriate stimulus exposure duration and using shorter durations may produce a floor effect.

Therefore, the experiment reported in this chapter examined the WSE of characters over pseudocharacters in more data-limiting viewing conditions by using visual masking

Visual masking is a widely adopted and powerful way of studying visual processes. A visual mask is a stimulus presented in order to impair the visibility of another stimulus, which is called the target. There are different ways of categorizing

masking. According to the temporal relationship between the target and the mask, there are forward masking (mask onset prior to target onset), simultaneous masking (simultaneous onset), and backward masking (mask onset after target onset). According to its spatial relationship with the target, masking can be divided into pattern masking and metacontrast masking. Pattern masking refers to when the mask directly interferes with the visual contents of the target. Metacontrast masking refers to the scenario in which the mask takes place in the surrounding environment of the target so that it is closely adjacent to but not overlapping with the target. For example, an open circle is used as metacontrasting mask for a target which has a smaller diameter than the circle (see Enns & Di Lollo, 2009 for more information). Enns and Di Lollo (2009) also noted that backward pattern masking is more commonly used when masking is needed as a tool for limiting visual access to the target over a controlled period of time. Accordingly, backward pattern masking was used in the present study to suit the practical purpose of using masking here, which is to limit the visibility of target stimuli.

There are two ways that backward pattern masking can affect visual recognition depending on the interval between the target and mask presentation, typically referred to as stimulus onset asynchrony (SOA). Masking can be used to disrupt the very early stages of visual processing, more specifically from the retina to the primary visual cortex with short SOAs (within approximately 100ms); alternatively, masking effect at longer SOAs is expected to interfere with the processing of target information when it travels through the higher visual network (see Bugmann & Taylor, 2005 and Enns & Di Lollo, 2009 for recent reviews). Backward pattern masking at shorter SOAs is similar to adding a visual noise at the same location to the signal (target) at early levels of visual representation, which is exactly what masking is intended for in the present study. It has been reported that masking with short SOAs has its maximal effect at a SOA of 0 ms

and has null effect beyond a SOA of approximately 100 ms (e.g., Breitmeyer, 1984; Kahneman, 1968; Turvey, 1973). On the other hand, recall that masking rather than filtering is used in the present study in order to keep the appearance of characters intact when visual access was limited. Based on these considerations, it was determined that mask presentation immediately follow target offset, i.e., a SOA of 17 ms (one frame).

As for the material for masking, there are two common ways of making visual masks in previous studies investigating word recognition. One way is to use random patterns unrelated to words, such as composed of shapes or hash signs (e.g., Dehaene, Naccache, Cohen, Bihan, Mangin, Poline, & Rivière, 2001; Grainger & Segui, 1990; Grainger, Colé & Segui, 1991). The other way is to use patterns related to words, such as composed of letter parts, superimposed letters or patterns composed of randomly rearranged fragments of the stimulus font (e.g., Hellige, 1983; Jordan et al., 2000; Marcel, 1983; Massaro & Klitzke, 1979; Wickens, 1972). There is evidence suggesting that the strength of masking is modulated by its global structure (e.g., Hermens & Herzog, 2007; Loffler, Gordon, Wilkinson, Goren, & Wilson, 2005). Loffler et al. (2005), in particular, found that the masking effect on face recognition was absent when the masks were of a completely irrelevant category (houses) and was strongest when the masks were of the same category as the targets (faces). When the masks (scrambled and inverted faces) shared partial similarity to the targets, a significant masking effect was obtained though less prominent than when upright faces were used. For this reason, it was determined that images sharing visual similarity with characters would be used as masks in the present study instead of using shapes or hash signs. Furthermore, since the primary purpose of the present study was to examine whether a character superiority over pseudocharacters would be observed in a more data-limited viewing condition, these two types of stimuli cannot be used as masks to avoid biased masking. Given the

above considerations, squares composed of re-arranged stroke fragments were prepared for masking purpose (see Section 5.2.2 below for methodological details). Although this sort of masks were visually more similar to the VM stimuli, as shown in Figure 5.1 and may result in biased masking for the VM condition, the possible biased masking is not important as far as the present experiment is concerned because the proceeding experiment successfully demonstrated a character and pseudocharacter superiority over VMs without masking.



Figure 5.1. An example of the masks used in Experiment 3. As described in the Methodology (see Section 5.2.2 for details), a unique mask was generated for each target right before its presentation by combining 81 randomly selected character fragments, each from a different character. An example of a mask is shown in the bottom row to illustrate how masks compared to character and VM stimuli. For the sake of space economy, 9 (instead of laying out 81) items were randomly selected from the character stimuli pool that were used in the experiment, as shown in the middle row. A fragment was then randomly selected from each of nine characters before they were randomly re-arranged into a  $3 \times 3$  fragment matrix to form the mask shown in the bottom row. Although both featuring stroke discontinuity, masks were distinct from VMs in that each mask came from different characters and bore no visual similarity or clue as to their source characters whereas each VM was specially tailored to contain the same amount of visual contents and similar coarse-scale information (overall outline and inter-radical interaction, in particular) as its corresponding character.

The hypothesis of the current experiment is as follows. First of all, since the masks were visually more similar to the VM stimuli as they were both made of stroke fragments, it is expected that identification performance to the VM condition would be more severely impaired compared to characters, pseudocharacters and inverted

characters. If the familiar coarse-scale configurational information in characters played a facilitatory role in their identification and if the activation at the character level provided beneficial feedback towards radical discrimination, the present experiment should observe more disrupted identification performance for pseudocharacters compared to characters, resulting in the WSE for characters over pseudocharacters. On the contrary, if the character and the pseudocharacter advantage over inverted characters found in the previous experiment was indeed of the same nature, namely, the inversion effect on the radical basis, the backward masking should have similar effect on both characters and pseudocharacters.

## 5.2 Methodology

### 5.2.1 Participants

A different group of eighteen participants (aged 19-30) took part in three sessions. All were native speakers of Chinese, reported normal or corrected to normal vision, and were screened using a Bailey-Lovie eye chart (Bailey & Lovie, 1976) for minimum binocular acuity of 3/3 or better.

### 5.2.2 Stimuli

The stimuli set was the same as used in Experiment 2. Specifically, there were four stimulus types, characters, pseudocharacters, inverted characters and VMs, each containing 200 test items under its own category. To prevent possible strategy learning through one and the same mask, a unique mask for each target was constructed in the following way. First, a fragment of  $0.1 \times 0.1^\circ$  was selected in a random position from each of the 200 characters used in Experiment 2 to obtain a pool of 200 fragments; then 81 (in a matrix of  $9 \times 9$ ) fragments were randomly selected from the pool and combined to form a mask sized at  $0.9 \times 0.9^\circ$  for each target display.

### 5.2.3 Visual conditions

Visual conditions were the same as used in Experiment 2. Specifically, Song was used as the typeface for the construction of stimuli, which were presented in black on a white background. Background luminance was 99cd/m<sup>2</sup> and stimulus luminance was 6cd/m<sup>2</sup>. Viewed from 35cm, stimuli subtended horizontal visual angles between 0.3 and 0.76 degrees, with a mean of approximately 0.5 degrees, which corresponded with the optimal retinal image size for normal Chinese reading established in Experiment 1 (refer back to Section 4.2.3 for explanations of stimulus width variations).

### 5.2.4 Apparatus

Apparatus was the same as used in Experiment 2. Stimuli were presented on a Samsung SyncMaster 753s monitor set to a resolution of 1280 x 1024. A Cambridge Research Systems VSG 2/5 card was used to control stimulus presentations and record reaction times via a Cambridge Research Systems CT3 response box. Participants were seated in a darkened booth and a chin-rest was used to ensure accurate viewing distance throughout the experiment.

### 5.2.5 Design

Experiment design was the same as in Experiment 2. Specifically, there were four stimulus conditions, namely, characters, pseudocharacters, VMs, and inverted characters, which made the four levels of the within-subject factor. There were 200 items under each experimental condition which were randomized and broken down into 3 lists (containing 66, 66, and 68 items, respectively). Lists were then grouped together to form 3 blocks of test items, each containing equal number of test items across conditions. That is, two blocks contained 66 items from each of the four stimulus conditions (altogether 264 trials in either of these blocks) and the other block contained 68 items from each stimulus condition (altogether 272 trials in this block). Items within

each block were quasi-randomized for each participant with the constraint that no more than 4 target stimuli of the same stimulus condition were shown in succession. In addition, the order in which these 3 blocks were presented was counterbalanced across participants. Response error rate was taken as the dependent measure.

### 5.2.6 Procedure

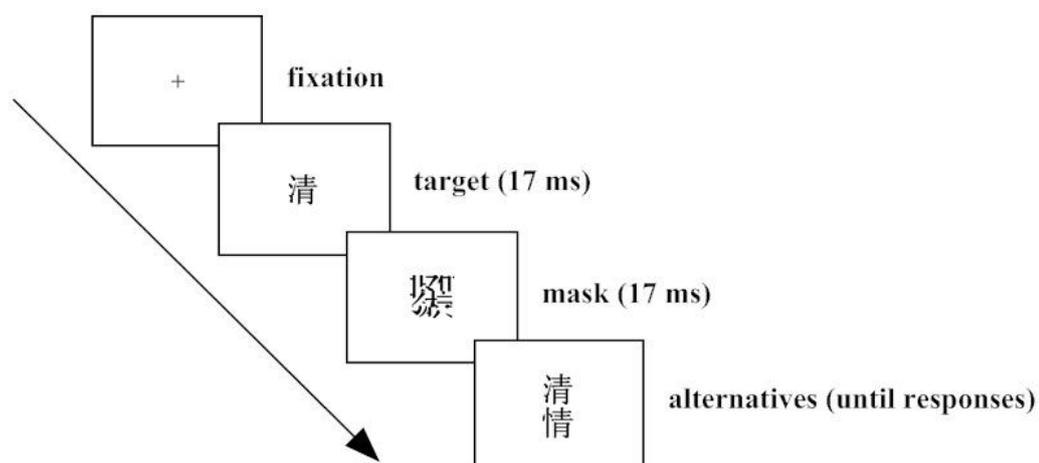


Figure 5.2. Trial procedure of Experiment 3 along the time line

Experiment procedure was the same as in Experiment 2 except that backward masking was applied to each target stimulus, as illustrated in Figure 5.2. Specifically, at the start of each trial a small fixation point appeared at the centre of the screen. As in Experiment 2, before initiating a target display, participants were only instructed orally and in writing to look at the central fixation point without the use of any eye tracker due to the fact of central presentation instead of lateralized presentation. When participants pressed either the top or the bottom button on the response box, the fixation point was immediately replaced by a target stimulus in the centre of the screen. Stimulus was presented for 17 ms, immediately followed by a mask. After 17 ms, the mask was replaced by two alternative choices, one above the other in the centre of the screen. The two alternatives remained on the screen until participants made a choice by pressing the

top or the bottom button to indicate that the top or the bottom item was the target stimulus that they had just been shown. There were 32 practice trials at the beginning of each block and participants took a 5-min break between blocks.

### 5.3 Results

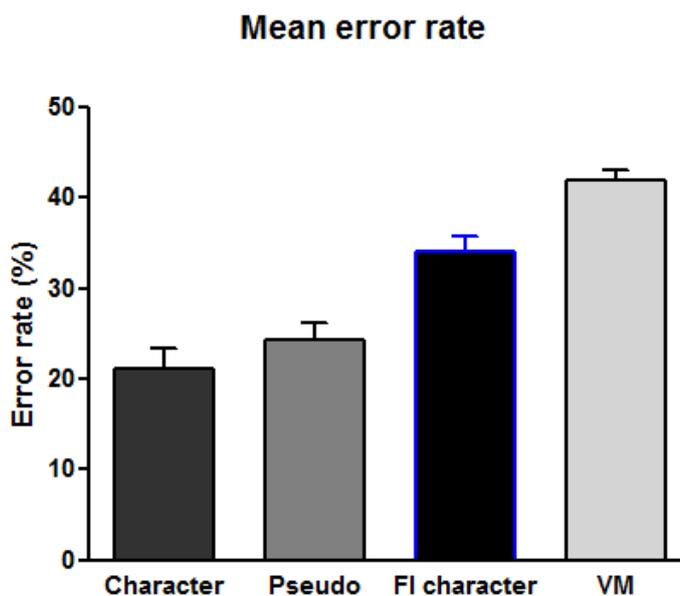


Figure 5.3. Mean error rate across experimental conditions in Experiment 3. 'FI' stands for 'fully inverted' and 'VM' for 'visual matches of characters'. Bars depict standard errors.

Mean identification error rate for each of the four experimental conditions is shown in Figure 5.3. One-way Repeated measure ANOVA showed a strong main effect of stimulus type ( $F_{(3,17)} = 83.44$ ,  $p < .001$ ,  $\eta_p^2 = .83$ ). Post-hoc t-tests revealed that identification performance was most accurate for characters (21% mean error rate) and pseudocharacters (24%) while not differing from each other, less accurate for inverted character (34%) and highest percentage of errors were made in response to VMs (42%). In comparison to performance in the proceeding experiment, mean error rate for characters and VMs showed a numeric drop of 1% and a numeric increase of

2%, respectively. Two unpaired t-tests with Welch's correction (not assuming equal variance) were performed to test if these two numeric differences were statistically significant. Results revealed that masking significantly affected VM identification ( $df = 27$ , Welch corrected  $t = 1.69$ ,  $p < .05$ ).

## 5.4 Discussion

In comparison to performance in the preceding experiment, backward masking seems to have impaired identification performance for the VMs (error rate from 40% to 42%) but not for the other three conditions. This may have been caused by the fact that the masks and the VMs were both made of stroke fragments. As mentioned in the introduction of this Chapter, existing research has shown that the strength of masking effect seems to be correlated with the similarity between the mask and the target (e.g., Hermens & Herzog, 2007; Loffler et al., 2005). The similarity between the masks and the VM stimuli resulted in a masking effect of 2% decrease in response accuracy compared to the results in the previous experiment. On the other hand, the masks and the VMs were distinct from each other by one fundamental dissimilarity. Specifically, the VMs were like shattered characters in that the strokes in characters were fragmented while the overall character outline was more or less maintained; whereas each mask was made by randomly selecting a fragmented part from each of randomly selected 81 VM stimuli and then randomly arranging them in a 9 x 9 square matrix. Therefore, the finding that identification accuracy for the VMs was close to 60% implies that the overall contour information in the VMs, though not as evident as in characters, still provided useful clues for participants to discriminate between alternative choices. Indeed, a paired t-test comparison confirmed that identification accuracy for VM stimuli was significantly better than pure guesswork (58% vs 50%,  $df = 19$ ,  $t = 7.40$ ,  $p < .001$ ).

No masking effect was observed for characters, pseudocharacters, or inverted characters. Indeed, masks were composed of very fine-grained high spatial frequency features and may not be able to exert any significant interference on the extraction and analysis of more coarse-scale low frequency information in characters, pseudocharacters and inverted characters when they were presented only for 17 ms. There is evidence in the literature that mask duration plays an important role in backward pattern masking. For example, in Hashimoto, Watanabe, Inui, Hoshiyama, Murase, & Kakigi (2006), targets were presented for a duration similar to the target duration used in the present experiment (16 ms vs. 17 ms), which were followed by masks presented for varied periods. Hashimoto et al. observed significant masking effect when masks were presented for 144 ms, obscured masking effect when masks were presented for 48 ms, and no masking effect when masks presented for 16 ms. In the present experiment, no masking effect was observed for characters, pseudocharacter or inverted characters when they were all presented for 17 ms. The implication is that longer mask presentation duration may be needed to obtain significant masking effect on the recognition of characters, pseudocharacters.

Findings to this point presents two directions in which further research can be conducted. One direction is to maintain the assumption that the character context was indeed superior to the pseudocharacter context for radical perception and to press on with the masking effect in the hope of eventually observing more impaired performance for pseudocharacters than for characters. As discussed above, the masks used in this experiment can be altered in different ways to see if significant masking effect would appear, e.g., by increasing mask presentation time, by making new masks that share greater visual similarity to characters and pseudocharacters, or even by combining both. If none of these alterations worked, there are still other methods of limiting visual

access (such as filtering and stimulus degradation, as mentioned in Section 4.4). Nevertheless, limiting visual access is only a tool of establishing the WSE of characters over pseudocharacters in Chinese character recognition, i.e., by observing differentially impaired character and pseudocharacter perception. An alternative route to take beyond this point is to reconsider the assumption of the WSE in Chinese. As discussed in Chapter 1, the superiority of word context in letter perception over pseudoword context is typically interpreted as reflecting a top-down facilitation, i.e., activation at the word level providing beneficial feedback towards the letter level. It is believed that the coarse-scale configurational information in characters is crucial to activating word representations, which is in accordance with the more general perceptual expertise effect. Two consecutive experiments (the previous chapter and the present chapter) failed to observe significant character superiority over pseudocharacters. The implication may be that the familiar coarse-scale configurational information in Chinese characters plays no beneficial role and that radicals are processed the same way in the character context as in the pseudocharacter context. If Chinese radicals were indeed processed individually regardless of context lexicality, then no significant WSE for characters should be observed not only when compared to pseudocharacters but also when compared to other non-lexical context conditions, which will be investigated in the next chapter.

## **Chapter 6. Character superiority over pseudocharacters investigated with semi-inversion of stimulus- Experiment 4**

### **6.1 Introduction**

As pseudocharacters were combinations of legal radicals in their illegal positions, they can be considered as upright radicals in an unfamiliar context. In a similar vein, inverted characters can be considered as the same radicals put upside down in an unfamiliar context. The pseudocharacter advantage over inverted characters found in Experiment 2 (Chapter 4) suggests that the inversion effect also applies to radical perception, i.e., radicals are processed as a whole when embedded in a non-lexical context. However, Experiment 2 and Experiment 3 (Chapters 4 and 5) both failed to obtain a significant character superiority over pseudocharacters, which implicates that the character advantage over inverted characters found in Experiment 2 may reflect an inversion effect on the radical basis rather than on the whole character basis.

Further to the discussion in the proceeding chapter, if radicals were processed completely independent of context lexicality, no WSE for Chinese characters would be observed not only when compared to pseudocharacters but also when compared to radicals embedded in other nonlexical contexts. For this reason, this chapter reports an experiment in which two new nonlexical contexts were introduced to further investigate radical perception and the WSE in Chinese. Specifically, the non-critical radicals in characters and pseudocharacters were inverted to form two types of nonlexical contexts for radical perception, which will be referred to as semi-inverted characters and semi-inverted pseudocharacters hereafter (see Figure 6.1). As introduced at the beginning of this thesis, the WSE also includes the word superiority over single letters, sometimes referred to as the word-letter effect. When the word-letter effect is investigated in the

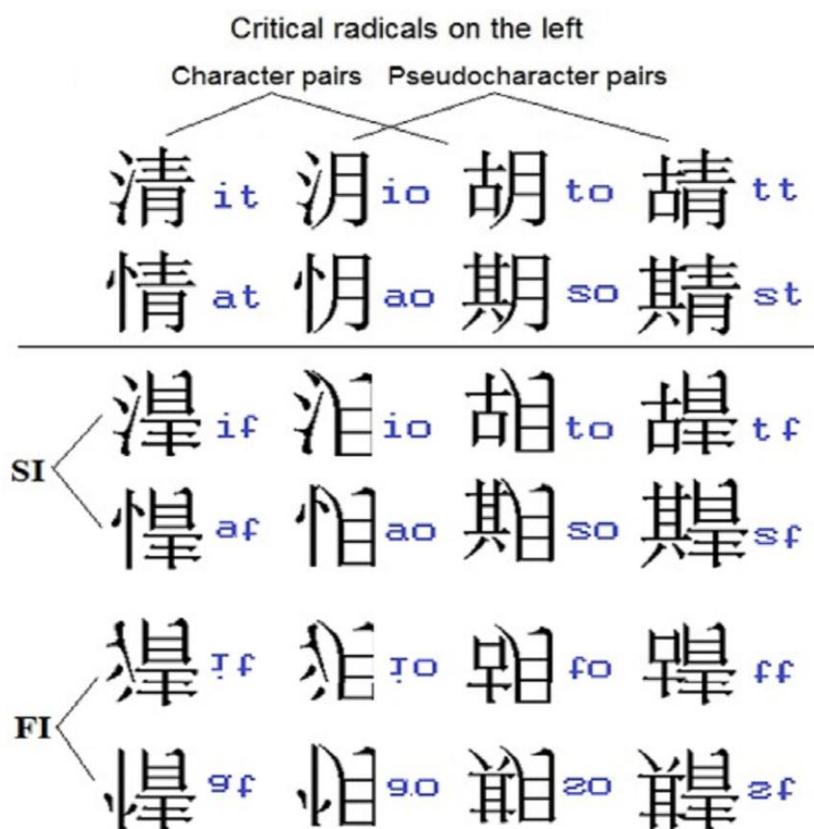


Figure 6.1. Sample stimuli from Experiment 4. Above the horizontal line are upright stimuli. SI stands for semi-inverted and FI for fully-inverted. The 2-letter strings are provided to help with understanding how radicals in characters are manipulated (replaced or inverted) to produce matched conditions.

existing literature, in order to imitate the visual complexity and the global structure of words, it is common to present single letters with ampersands or hash signs as gap fillers in locations that correspond to the letter positions other than where the critical letter occurs in the word condition. Take the word 'read' for example. Participants will see and respond to 'read' vs. 'r&&&', '&e&&', '&&a&' or '&&&d' depending on which letter position is examined for the word-letter effect. In this sense, the two semi-inverted conditions included in the present experiment are analogical to the single letter condition in studies investigating the word-letter effect. In the two semi-inverted conditions, the remaining space other than the critical radical is filled by an inverted radical, which would be more appropriate than ampersands and hash signs by providing

exactly matched amount of visual contents (in terms of amount of pixels) and highly similar structure (i.e., a stroke cluster with various spatial features). It is important to note that there has been no published work investigating the WSE of characters over single radicals. Finally, since it was well-established in the two preceding experiments that the VM condition provided a more inferior context for radical discrimination compared to characters, pseudocharacters, and inverted characters, the VM stimuli were replaced by inverted pseudocharacters which was expected to serve as a better control condition.

Therefore, there were six stimulus conditions in this experiment, i.e., characters, pseudocharacters, semi-inverted characters, semi-inverted pseudocharacter, fully-inverted characters, and fully-inverted pseudocharacters. If Chinese readers indeed perceived radicals independent of their context, no matter the context being lexical or not, characters, pseudocharacters and the two semi-inverted conditions should produce similar level of identification performance as they each provided a distinct context for upright radical perception. Fully-inverted characters and fully-inverted pseudocharacters each provided a context for inverted radicals. It was therefore expected that they should produce similar level of response accuracy, which would be poorer relative to the four upright-radical conditions.

## 6.2 Methodology

### 6.2.1 Participants

Twenty-four participants (aged 21-26) took part in three sessions. All were native speakers of Chinese, reported normal or corrected to normal vision, and were screened using a Bailey-Lovie eye chart (Bailey & Lovie, 1976) for minimum binocular acuity of 3/3 or better.

### 6.2.2 Stimuli

The 200 characters and 200 pseudocharacters used in Experiments 2 and 3 were kept in the present experiment, all of which were fully-inverted to get 400 fully-inverted stimuli. Additionally, the non-critical radicals in characters and pseudocharacters stimuli were inverted while the critical radical remaining upright to get 400 semi-inverted stimuli. Examples of stimuli under each of the six stimulus conditions were already shown above in Figure 6.1 (see Appendices 1 and 2 for more stimuli).

### 6.2.3 Visual conditions

Visual conditions were the same as used in Experiments 2 and 3. Specifically, Song was used as the typeface for the construction of stimuli, which were presented in black on a white background. Background luminance was 99cd/m<sup>2</sup> and stimulus luminance was 6cd/m<sup>2</sup>. Viewed from 35cm, stimuli subtended horizontal visual angles between 0.3 and 0.76 degrees, with a mean of approximately 0.5 degrees, which corresponded with the optimal retinal image size for normal Chinese reading established in Experiment 1 (refer back to Section 4.2.3 for explanations of stimulus width variations).

### 6.2.4 Apparatus

Visual conditions was the same as used in Experiments 2 and 3. All stimuli were presented on a Samsung SyncMaster 753s monitor set to a resolution of 1280 x 1024. A Cambridge Research Systems VSG 2/5 card was used to control stimulus presentations and record reaction times via a Cambridge Research Systems CT3 response box. Participants were seated in a darkened booth and a chin-rest was used to ensure accurate viewing distance throughout the experiment.

### 6.2.5 Design

There were six stimulus conditions in the present experiment, characters,

pseudocharacters, semi-inverted characters, semi-inverted pseudocharacters, fully-inverted characters and fully-inverted pseudocharacters. A similar blocked randomization design as in Experiments 2 and 3 was used to generate stimulus lists. Specifically, there were 200 items under each experimental condition which were randomized and broken down into 3 lists (containing 66, 66, and 68 items, respectively). Lists were then grouped together to form 3 blocks of test items, each containing equal number of test items across conditions. That is, two blocks contained 66 items from each of the six stimulus conditions and the other block contained 68 items from each stimulus condition. Items within each block were quasi-randomized for each participant with the constraint that no more than 4 target stimuli of the same stimulus condition were shown in succession. In addition, the order in which these 3 blocks were presented was counterbalanced across participants. Response error rate and time were taken as repeated measures.

#### 6.2.6 Procedure

Experiment procedure was the same as in Experiment 2, as shown previously in Figure 4.3. Specifically, at the start of each trial a small fixation point appeared at the centre of the screen. Before initiating a target display, participants were instructed orally and in writing to look at the central fixation point without the use of any eye tracker due to the fact of central presentation instead of lateralized presentation. When participants pressed either the top or the bottom button on the response box, the fixation point was immediately replaced by a target stimulus in the centre of the screen. Stimulus was presented for 17 ms, immediately followed by a mask. After 17 ms, the mask was replaced by two alternative choices, one above the other in the centre of the screen. The two alternatives remained on the screen until participants made a choice by pressing the top or the bottom button to indicate that the top or the bottom item was the target

stimulus that they had just been shown. There were 32 practice trials at the beginning of each block and participants took a 5-min break between blocks.

### 6.3 Results

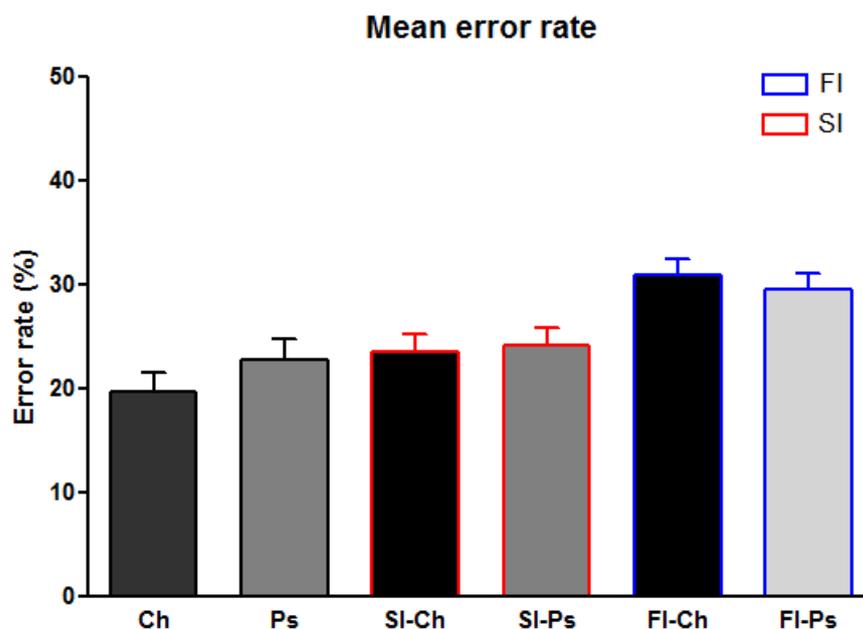


Figure 6.2. Mean error rate across experimental conditions in Experiment 4. 'Ch' stands for 'characters', 'Ps' for 'pseudocharacters', 'SI' for 'semi-inverted', and 'FI' for 'fully-inverted'. Bars depict standard errors.

Mean identification error rate for each of the four experimental conditions is shown in Figure 6.2. One-way Repeated measures ANOVA showed a strong main effect of stimulus type ( $F_{(5,23)} = 43.56, p < .01, \eta_p^2 = .65$ ). Post-hoc t-tests revealed that characters produced the best identification performance (20% mean error rate), followed by pseudocharacters (23%), semi-inverted characters (24%) and semi-inverted pseudocharacters (24%) which did not show any significant difference between themselves. Highest percentage of errors were made in response to fully-inverted characters (31%) and fully-inverted pseudocharacters (30%) and they did not differ from each other. Similar pattern of results was found by a  $2 \times 3$  repeated measures

ANOVA with stimulus (characters, pseudocharacters) and inversion (no inversion, semi-inversion, full inversion) being the within-subject factors. Specifically, a main effect of inversion ( $F_{(2,23)} = 77.57, p < .01, \eta_p^2 = .77$ ) and an interaction between stimulus and inversion ( $F_{(2,23)} = 6.62, p < .01, \eta_p^2 = .22$ ) were found significant. Post-hoc t-tests for the inversion effect showed that participants were more accurate in responses to upright stimuli (no inversion) relative to semi-inverted stimuli and identification performance was poorest in response to fully-inverted stimuli (all  $ps < .01$ ). Post-hoc comparisons for the interaction effect further revealed that the trend as found in the main effect of inversion was significant on characters whereas upright pseudocharacters did not differ from semi-inverted pseudocharacters although both showing advantage over fully-inverted characters. Besides, the character advantage over pseudocharacters was obtained only when there was no inversion (all  $ps < .01$ ).

## 6.4 Discussion

The most important finding of the present experiment is the significant WSE of Chinese characters over pseudocharacters. This supports the argument that the lexicality of the context in which a radical is contained affects its recognition. Recall that pseudocharacters were made by replacing one of the two component radicals in left-right structured characters with another radical which can appear in that particular position yet never in combination with the other radical in the original character. For any given pseudocharacter, the positional regularity of radicals means that Chinese readers are used to seeing the radical on the left being on the left and right on the right and therefore familiar with the visual patterns along the left-most and the right-most margins of that pseudocharacter. However, the 'made-up' combination of the two component radicals means that the complete outline (not just the left-most and the right-

most margins of a pseudocharacter), the spatial arrangement of strokes from either radical at the top and the bottom, and the inter-radical interactions have never been encountered before and have no representations in the visual system. In contrast, such coarse-scale configurational information in characters is familiar to Chinese readers and therefore is highly utilizable to efficiently determine character identities.

Experiments 2 and 3 failed to obtain significant WSE of characters over pseudocharacters despite a numeric difference of similar size (2-3% error rate) between the two conditions. The three experiments were conducted by using the same experimental task in the same procedure (except the additional step of backward making in Experiment 3) with the same visual conditions. Therefore, differences in the other two respects, namely, number of participants (sample size) and stimulus conditions (stimuli composition), may be responsible for the discrepancy in the results of the present experiment and its two proceeding experiments.

Indeed, there is evidence that the composition of stimuli may affect participants' performance by causing biased responses towards one particular stimulus condition. For example, Carr, et al. (1978) presented words, pseudowords and nonwords in different proportions over three blocks of trials while manipulating participants' expectations as to which type of stimuli would be shown more often or exclusively in a particular block of trials. The results showed that when participants expected to see different types of stimuli with one more often than the other two, identification performance was similar for words and pseudowords which were both identified more accurately than nonwords no matter which exact stimulus type was expected. In contrast, when participants were led to expect only one type of stimuli while the other two types of stimuli were shown surreptitiously on a small number of trials, their responses to pseudowords were affected by their expectation and the composition of stimuli. Specifically, when

participants expected to see only words or nonwords, identification performance for pseudowords did not differ from that for nonwords; only when pseudowords were expected, the pseudoword advantage over nonwords appeared. Carr et al. argued that there are two mechanisms of processing letter strings, i.e., the lexical mechanism which is exclusive to words and the orthographic computation mechanism which is available to pseudowords. The lexical mechanism was working regardless of participants' expectation or stimuli composition whereas the unexpected pseudowords failed to efficiently activate the orthographic computation. However, the argument of Carr et al. does not apply to the present scenario. For one thing, although the composition of stimuli in the present experiment was changed from containing four stimulus types in two preceding experiments to containing six stimulus types with increased proportion of nonlexical items, participants' subjective expectation was not manipulated. More importantly, the change in stimuli composition did not affect how well participants responded to characters or pseudocharacters. In other words, the character superiority over pseudocharacters was not obtained because the change in stimuli composition favoured the processing of characters or disfavoured the processing of pseudocharacters. The identification accuracy in response to both stimulus conditions was similar to that observed in the previous experiments, which accordingly led to a similar size of difference between the two conditions.

The above discussion clearly shows that the discrepancy between the results of the present experiment and the results of its two processors was not caused by the change in stimuli composition. The only other methodological difference between the three experiments was the overall number of trials under each condition. Although the same 200 character items and the same 200 pseudocharacter items were used in the present experiment, sample size increased from 18 to 24 participants and accordingly

the overall number of trials from 3600 to 4800 for either condition. The increased number of trials may have brought statistical significance to the numeric difference between characters and pseudocharacters in the previous two experiments. This sample size speculation will be further supported in the next experiment.

The size of the character superiority over pseudocharacters in the present study (3%) was seemingly inconsistent with previous findings. Cheng (1981) found approximately 8% character superiority over pseudocharacters using a two-alternative forced choice task. The discrepancy in the size of character superiority over pseudocharacters between the present study and Cheng (1981) may have been caused by the extremely short stimulus exposure duration used in the latter. Specifically, stimuli were presented only for 6.6 ms in Cheng (1981) and the highest response accuracy was observed for characters at 62.5%, followed by 54% for pseudocharacters and 45% for noncharacters which were near and below 50%, respectively. In contrast, the 17 ms stimulus exposure duration used in the present study was more reasonable as it ensured 75% accuracy across conditions and thus avoided ceiling or floor performance.

The present study also found better performance for characters than for semi-inverted characters and semi-inverted pseudocharacters. It was noted in the introduction of this chapter that the two semi-inverted conditions were analogical to the letter condition in studies investigating the WSE over single letters in that they both consisted of a radical and an inverted radical as gap-filler in the other radical position. The character advantage over the semi-inverted conditions observed here thus can be taken as evidence of the WSE of character over single radicals, which has never been reported in published studies before. On the other hand, identification performance in response to the two semi-inverted conditions did not differ from that in response to

pseudocharacters and accordingly only a 4% character superiority was observed over single radicals. This superiority size seems considerably small compared to the findings in studies using English stimuli. Specifically, the existing literature has typically shown a 10-15% word superiority over single letters, which is considerably larger than the 4% character superiority over radicals observed in the present experiment (e.g., Carr et al., 1978; McClelland & Johnson, 1977; Samuel et al., 1982). Besides, when words, pseudowords and single letters are all included in the comparison, the word superiority over single letters is often accompanied by a pseudoword superiority over letters at the same time (e.g., Carr et al., 1978). However, most of the studies comparing letter perception in word context against when presented alone used words of 4 or more letters as they are more representative of the words encountered in everyday reading; when word length was manipulated, the shortest length usually started from 3 letters (refer back to Section 1.3.2 for details). In the rare case when stimuli contained 2-letter words, a smaller word-letter difference was reported. For example, Samuel et al. (1982) found that the size of the WSE over single letters decreased from 15% for 4-letter words to 10.2% for 3-letter words and to 3.4% for 2-letter words, which is similar to the size of the character superiority over single radicals found in the present study. Despite the differences between the two languages set out in Section 2.1.2, left-right structured Chinese characters and 2-letter English words share the compositional similarity that they both can be decomposed into two lower-level elements (radicals and letters). If the comparable sizes of character superiority over radicals and the 2-letter word superiority over letters can be indeed associated with the compositional similarity between the two types of linguistic stimuli, the seemingly inconsistency that no counterpart pseudocharacter-radical effect was observed between for the (typically 4-letter) pseudoword superiority over single letters may be attributed to the difference in the

number of lower-level components (2 radicals vs. 4 letters). However, this speculation cannot find any empirical support as none of the existing studies has investigated if letters would be identified more accurately in 2-letter pseudowords than in isolation or more generally if variations in the length of pseudowords would have an impact on the pseudoword superiority over single letters (as noted earlier, typically obtained by using 4-letter pseudowords). If that was not the case and decreasing pseudoword length from 4 letters to 2 letters did not eliminate or reduce its advantage over single letters, the relatively smaller character-radical difference and the absence of pseudocharacter superiority over radicals in the present study more likely reflects certain language-specific features of Chinese.

Finally, the inversion effect in character recognition found in Chapter 4 was replicated here. More importantly, the finding that the two fully-inverted conditions did not differ from each other suggests that the perception of inverted radicals, like upright radicals, is not affected by the context in which they are embedded. Even when a context provides the same level of visual intensity (in terms of number of pixels and luminance) as a character, it no longer benefits discrimination of its components compared to other contexts so long as the lexicality is removed by semi or full inversion of the character.

## 6.5 Summary and motivations for the next experiment

To sum up, findings of the present experiment show that radical perception is significantly influenced by the lexicality of the visual context in which it is contained. The well-established WSE in English also applies to Chinese reading in that radicals are identified more accurately in characters than in pseudocharacters or in isolation. Together with the inversion effect, the WSE shows that the familiar global

configurational information in characters (and words) plays an important role in their identification. When this familiar information is disrupted to various levels, as by inverting the whole character, replacing component radical with another radical (resulting in a non-existing combination of radicals) or a nonradical (inverted radical), identification performance is accordingly impaired at various levels. Indeed, some studies in the literature have shown the importance of global configurational information by manipulating readers' attention instead of this visual information itself. For example, Chastain (1982) and Johnston and McClelland (1974) both induced participants to focus on single letters in words and found that the same letters were identified more accurately when participants attended to the whole word than when they focused their attention just on those individual letters.

Finding of the present experiment also provides a straightforward motivation for the next experiment, i.e., to investigate if the character superiority also exists with lateralized presentation and if the visual field (LVF or RVF) has a significant impact on the processing of characters and character-like stimuli. As mentioned in Chapter 1, studies using English stimuli show that words are perceived more accurately when they are presented in the RVF than when they are presented in the LVF whereas nonword performance is not affected by the visual field of presentation, which led to the absence of WSE in the LVF (refer back to Section 1.5). Since it is well-established that extrafoveally presented stimuli in either visual field initially project to its contralateral hemisphere, the RVF advantage has been taken as evidence in support of a dominant role of the LH in word processing. In a similar vein, presenting characters and character-like stimuli extrafoveally will shed light on whether the processing of Chinese characters is dominated by one hemisphere and if yes, whether this hemispheric asymmetry also applied to the processing of character-like stimuli.

Furthermore, the recent debate between the 'unilateral projection' view and the 'bilateral projection' view of stimuli shown to either side of central fixation within the fovea has involved using Chinese characters as testing ground by comparing naming and homophone judgement responses to centrally presented SP and PS characters (semantic-phonetic and phonetic-semantic radical combination, respectively) (Hsiao & Shillcock, 2005; Hsiao, Shillcock, & Lee, 2007). This provides a second motivation for the next experiment for two reasons (see Section 7.2.2 for details). Firstly, Hsiao and colleagues decided to use the naming task for the reason that it "has been shown to produce robust laterality effects" compared to tasks that do not demand phonological processing. Paradoxically, the same reason exactly explains why the naming task is inappropriate for assessing the hemispheric asymmetries in visual character recognition as it will bias activations in one hemisphere (the LH). Secondly, the validity and credibility of Hsiao and colleagues' work was also undermined by presenting characters in central vision. Recall the characteristics of Chinese characters introduced in Section 2.1.2 that the two radicals in SP/PS compound characters are rarely equally sized (in terms of width) and there is rarely a vertical gap between the two component radicals. As a consequence of the unequal radical sizing and the radical interactive-ness features of Chinese characters, central fixation (monitored by an eye-tracker or not) does not ensure that either radical initially projects to one or both hemispheres in its entirety without manually altering the size proportion of the two radicals or tearing the two radicals apart within characters. A more appropriate way of addressing the 'unilateral projection' versus the 'bilateral projection' dispute in Chinese character recognition is therefore to present stimuli to either side of the fixation point within the fovea. Indeed, the square-shaped compactness of Chinese characters (around 0.5 degrees at normal reading distance) makes them ideal for this way of investigation.

Finally, behavioural responses are the outcome of a sequence of complex brain processes and do not provide direct answer to the question that whether characters foveally presented to either side of the fixation point initially project to the contralateral hemisphere or both hemispheres. Therefore, the ERP technique will be incorporated in the next experiment in order to more closely examine hemispheric activities in the early stages of character processing and how the patterns of these activities evolve over time to affect the ultimate behavioural results.

## **Chapter 7. Character superiority over pseudocharacters in lateralized display and its neural correlates - Experiment 5**

### 7.1 Introduction to electroencephalogram

#### 7.1.1 EEG, ERP and VEP

Electroencephalogram, or EEG, was first reported by Berger (1929) in which electrical voltages of the the human brain was recorded from an electrode placed on the scalp and then amplified and plotted over time. Event-related potentials (ERPs) refers to those neural responses associated with stimulation from certain sensory, cognitive or motor events, which can be extracted from the EEG by averaging. ERP research started focusing on sensory issues until the first cognitive ERP (the contingent negative variation) was reported by Walter and colleagues in 1964. Over the decades, various more cognitive ERP components were identified and the technique has proved to be very useful in both scientific and clinical applications. Most research in cognitive neuroscience now uses the term ERP, however, other terms may be occasionally encountered especially in other fields. Relative to the present study is the term VEP (visual evoked potential). VEP is commonly used in clinical contexts to describe very early sensory ERPs elicited by visual stimuli that are used to assess pathology in the visual system.

#### 7.1.2 Major ERP components in experiments with visually presented linguistic stimuli

**C1** The C1 is the earliest identifiable human VEP reported in the literature with an onset latency around 50 ms and peak latency between 60-100 ms. Based on the observation that its polarity reversal corresponds to the retinotopic organization of the striate cortex, it is generally believed that the C1 originates from the primary visual

cortex within the calcarine fissure. Specifically, the part of area V1 that codes the lower visual field is on the upper bank of the fissure and the part that codes the upper visual field is on the lower bank. As a result, the voltage recorded on the scalp above the calcarine fissure is positive for stimuli in the lower visual field and negative for stimuli in the upper visual field (e.g., Clark, Fan, & Hillyard, 1995; Jeffreys & Axford, 1972). However, the division of the lower visual field and the upper visual field is not exactly at the horizontal midline. Clark et al. (1995) manipulated the eccentricity of stimulus presentation along the horizontal midline and found that the C1's polarity remained negative until 15-20deg in the lower visual field. Another notable observation of the C1 is its relatively weak strength not only in VEP studies but also in MEG and fMRI studies. For example, Meredith and Celesia (1982) used full central field stimulation of 2deg 18' and found that the earliest component N1 (negativity with mean peak latency around 75 ms) was absent in some of the subjects with a mean peak amplitude of only  $\sim 0.6 \mu\text{V}$ . Shigeto, Tobimatsu, Yamamoto, Kobayashi & Kato (1998) reported the lowest incidence of detectable N75m (corresponding to the C1 here) and the least reliability of its dipole estimation among the early VEPs. Consequently, most, if not all, language-related ERP studies have skipped the C1 and described the P1 as the first major neural response after stimulus presentation.

**P1** Immediately following the C1 is the P1, the first major positive deflection of human VEP recorded at lateral occipital electrode sites with a typical onset between 60-90 ms post-stimulus and typical peak between 100-150 ms. Therefore, this wave has also been termed as the 'P100' or 'P150' by some researchers. It is generally believed that the P1 originates from the extrastriate cortex (BA18 and BA19). Some studies also differentiated between two phases of the P1, the early phase arising from dorsal extrastriate cortex (in the middle occipital gyrus) whereas the later phase arising more

ventrally from the fusiform gyrus (e.g., Russo, Martinez, Sereno, Pitzalis & Hillyard, 2001). Like the C1, the P1 has proven to be sensitive to variations in the physical parameters of stimulus such as size, eccentricity and duration of stimulus presentation. For example, Busch, Debener, Kranczioch, Engel, & Herrmann (2004) observed increased P1 amplitude and decreased P1 latency with stimulus size as well as decreased P1 amplitude with presentation eccentricity. Mercure, Dick, Halit, Kaufman, & Johnson (2008) observed greater P1 amplitude for longer presentation duration. Furthermore, some sorts of top-down influences start to show through during this period. For example, Hillyard, Vogel, & Luck (1998) found that the P1 amplitude was modulated by spatial attention with higher P1 amplitude to attended stimuli than to unattended stimuli. Proverbio & Adorni (2009) obtained evidence that cognitive task has an impact on the P1 with the letter detection task eliciting greater P1 than the lexical decision task.

**N1** Immediately following the P1 is the N1, the first major negative wave of human VEP. There are several subcomponents of the N1 and relevant to the present study is a strong posterior negativity recorded at lateral occipito-temporal sites. Since this lateral occipito-parietal negativity typically peaks between 150-200 ms, it has also been referred to as the 'N150', 'N170' or 'N200' depending on its peak latency in a particular study. One of the major findings on the N1 component is the brain's sensitivity to visual stimuli of certain categories at this period, most notably to face stimuli. Specifically, familiar faces elicit greater N1 than unfamiliar faces and faces elicit greater N1 compared to stimuli of other categories like words, especially over the right hemisphere (e.g., Bentin et al., 1996; Rossion et al., 1999; Rossion, Joyce, Cottrell, & Tarr, 2003). The N1 is therefore believed by many as being selectively elicited by face stimuli and referred to as the face N170. However, there have recently appeared an

increasing number of studies which show that the N1 is also highly sensitive to word stimuli especially in the left hemisphere. Indeed, it remains a much-debated question whether the face and word associated effects observed in the N1 are due to the human brain's functional specificity to stimuli of certain categories only or to some general perceptual expertise.

C1, P1 and N1 are traditionally categorized as exogenous components in that their presence in human VEP/ERP is task-independent and their amplitude and/or latency are highly sensitive to the physical parameters of the eliciting stimuli; In contrast, endogenous components refer to those that appear in certain tasks with latency and/or amplitude more sensitive to internal cognitive factors.

**P2** Immediately following the N1 is the P2, the second major positive ERP to visual stimuli. It is typically observed within the time window of 200-300 ms post-stimulus onset over midline frontal, central and parietal sites with maximal strength over the frontal region. The P2 has mainly been studied in relation to visual search and attention, memory and repetition effects, etc. (e.g., Gruber & Müller, 2004; Hillyard & Münte, 1984; Luck & Hillyard, 1994; Maeno, Gjini, Iramina, Eto, & Ueno, 2004;). In the area of word or character recognition, there is evidence linking the P2 with different aspects of word processing (orthographic: e.g., Liu, Perfetti, & Hart, 2003; phonological: e.g., Zhang, Zhang & Kong, 2009; lexical retrieval: e.g., Liu, Perfetti, & Wang, 2006) However, as pointed out in a recent review (Crowley & Colrain, 2004), unlike the N1 or the other late ERPs, little work has been done on the P2 to elucidate the generation mechanisms, the cognitive correlates or its functional significance in general. It is also noteworthy that the P2 has often been discussed as the tail end of the N1/P2 complex or the 'vertex positive potential' (VPP) until some recent studies supporting its role as an independent component with distinct features such as its persistence from wakefulness

into sleep and its increased amplitude with aging, and its occurrence with respiratory stimuli (see Crowley & Colrain, 2004 for review and discussion).

**P3** The most-studied endogenous component in the entire ERP literature is the P3. The P3 (or P300, the third major positive wave) is a broad positive potential with a typical peak latency between 300 and 400 ms post-stimulus in any sensory modality with maximum strength observed along the parieto-occipital midline, especially at the Pz site. It was first reported in the 1960s (Desmedt, Debecker, & Manil, 1965; Sutton, Braren, Zubin, & John, 1965) in a task known as the odd-ball paradigm and then later observed in many other tasks (for reviews, see Hruby & Marsalek, 2003; Nieuwenhuis, Aston-Jones, & Cohen, 2005; Picton, 1992; and Pritchard, 1981). A large bulk of research has attempted to associate variations in the P3's latency and amplitude to several lines of cognitive factors such as stimulus probability, expectancy and novelty, attention and task relevance, task difficulty and participants' confidence or uncertainty level, though there is also evidence that the P3 wave is modulated by the physical characteristics of stimuli like modality, size and presentation time. In addition, the P3 wave proves to be more pronounced in tasks demanding more decision-making, ranging from the more generic odd-ball, go/no-go, size or orientation judgement tasks to the more verbal-specific ones like lexical, phonological or semantic decision tasks. Indeed, Nieuwenhuis et al.'s recent review comments that the P3 reflects the brain's response to the outcome of stimulus evaluation and internal decision-making processes.

**N400** The N400 is a broad negative deflection peaking after 400 ms with scalp maximum often observed at the temporo-parietal sites. It was initially known as a context-dependent component so that larger negativity was elicited when the meaning of a target word is incongruent with the context of a sentence as in a sentence reading task, or with the meaning of a preceding prime word as in a semantic priming task (e.g.

Kutas & Hillyard, 1980; Kutas & Hillyard, 1984; Rugg, 1987). Later it was found that the N400 can also be elicited outside semantic anomaly using single isolated stimuli like single words and even pseudowords (e.g., Bentin, McCarthy & Wood, 1985; Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999). The N400 has long been considered as a language-related ERP, though some studies reported similar waves using non-verbal stimuli like faces, pictures and environmental sounds.

### 7.1.3 Advantages and limitations of the ERP technique

When compared to behavioral measures, the ERP technique has the advantage of providing a continuous online measure of brain activities and thus is very useful to determine which stage or stages (even pre-stimulus stages when of interest) of processing are affected by a specific experimental manipulation. In contrast, a behavioral response reflects the output of a sequence of individual processes. As a consequence of this distinction, the ERP results of a particular study, especially during the initial stages after stimulus onset, are not always (partially or fully) consistent with the ultimate behavioral results or, vice versa, the behavioral results are not always (partially or fully) reflected in every stage of the ERP data. This inconsistency has been shown in various studies, including those investigating the WSE and hemispheric asymmetries in word recognition, in the following ways. One possibility is that the behavioral results of a study shows certain effect whereas no corresponding ERP evidence is observed or vice versa. For example, Evans & Federmeier (2007, 2009) investigated hemispheric asymmetries in verbal memory by asking participants to decide whether a test word presented in central vision had been previously presented in the left or right visual field. Both studies found that the accuracy of behavioral responses was better for words originally presented in the RVF whereas the ERP results of the former study showed a RH dominance and no ERP evidence of hemispheric

asymmetries was observed in the latter study (up to 800 ms post stimulus-onset). Comparing responses of prefrontally-impaired patients and healthy controls to repeatedly presented words and pseudowords, Swick (1998) observed a reduced ERP repetition effect whereas behavioral results showed intact lexical decision accuracy in patients. Another possibility of inconsistency between ERP and behavioral results is that certain experimental manipulation is shown to affect both ERP and behavioral response yet in different ways. For example, Martin et al. (2006) compared how participants responded to words and pseudowords presented for two durations (55 ms and 66 ms). They observed higher identification accuracy for words relative to pseudowords irrespective of presentation duration whereas an ERP effect of stimulus was evident only in one of the examined components (N1) and only when stimuli were presented for 66 ms. Compared to behavioral measures, the most obvious disadvantage of ERP is that it is relatively less clear and straightforward to interpret the functional significance of an ERP response (see Luck, 2005 for more detailed discussion).

When compared with other neurophysiological techniques, ERP stands out for its excellent temporal resolution. Modern models of EEG/ERP system typically record on millisecond basis. The most denounced drawback of ERP is its limitations in providing source informations, especially when compared against fMRI. The fMRI technique renders more direct images of which brain areas are activated by measuring hemodynamic responses with millimetre resolution. In contrast, scalp-recorded ERP signal results from co-activities of multiple sources containing numerous neurons including those remote from the recording electrode. The voltage strength is often attenuated or blurred due to low conductivity of the skull and other brain tissues (Cacioppo, Tassinari, & Berntson, 2007; Wang, Barber, Kakigi, Kaneoke, Okusa, &

Wen, 2001). In addition, the distribution of electrical fields may appear distorted due to the convoluted structure of the brain, one consequence being paradoxical lateralization which shall be discussed in more detail later. However, although the recording sites where an ERP response is observed cannot be taken for granted as the responsible sources and the inverse problem remains a massive challenge, there have been significant developments in minimizing electric source imaging errors since ERP's early days. Im, Gururajan, Zhang, Chen, & He (2007) recently evaluated the EEG source localization accuracy by comparing the V1 source locations estimated from fMRI and EEG corresponding to different visual stimuli with varied visual fields and found the mean location error was 7 mm between the fMRI-determined activation centres in V1 and the EEG source imaging activation peak estimated at equivalent C1 components (peak latency:  $74.8 \pm 10.6$  ms).

## 7.2 Background and aims of the present study

### 7.2.1 An overview of behavioral studies investigating the word superiority effect in lateralized display

#### 7.2.1.1 English

It is well-established that information presented to the left and right sides of each retina outside the fovea initially projects to the contralateral hemisphere. This anatomical arrangement of the human visual system provides the basis of psychophysical studies investigating hemispheric asymmetries in word processing in people with normal intact brains (see Posner & Raichle, 1994, for a review). By briefly presenting words in the left visual field (LVF) and the right visual field (RVF) and comparing behavioral measures (RT and accuracy) taken under different experimental conditions, researchers have established a wealth of evidence in support of the argument that the left

hemisphere (LH) plays a dominant role in language processing relative to the right hemisphere (RH). Besides observations of this phenomenon when word recognition performance in the two visual fields in the most straightforward experimental designs is compared (e.g., Moscovitch, 1973; Springer, 1977; White, 1969), one major line of evidence came from the well-known 'word length effect' which refers to the observation that increasing the number of letters in words increased the lexical decision and naming response latencies for words presented in the LVF but words presented in the RVF were largely unaffected (e.g., Bruyer & Janlin, 1989; Bub & Lewine, 1988; Chiarello, Maxfield, Richards, & Kahan, 1995; Ellis, Young, & Anderson, 1988; Eng & Hellige, 1994; Eviatar & Zaidel, 1991; Iacoboni & Zaidel, 1996; Young & Ellis, 1985). In a similar vein, researchers have demonstrated effects of the number of words that can be created by changing one single letter of a target word on lexical decision responses to that word (orthographic neighbourhood size effects) when presented in the LVF and the CVF (central visual field) but not when presented in the RVF (e.g., Lavidor & Ellis, 2002; Mano, Patrick, Andresen, Capizzi, Biagioli, & Osmon, 2010). Furthermore, researchers have also observed both word length effects and orthographic neighbourhood size effects in the RVF when word stimuli were shown in mixed cases (e.g. cAsE aLtErNaTiOn). These findings suggest that there exists a unique mechanism in the LH for word processing and this unique mechanism is not accessible to words with disrupted orthography.

Regarding the context effect on word recognition in lateralized displays, one representative study is Jordan, Patching & Milner (2000). In a series of experiments, the authors investigated word and nonword processing in the LVF and the RVF with the Reicher-Wheeler task to suppress influences of guesswork and an eye-tracker to ensure that participants did fixate the central fixation point and stimuli were indeed viewed in

the LVF or the RVF. The WSE was obtained with both masked and nonmasked displays only in the RVF. It should be noted that although studies prior to that had shown word-nonword effects for both visual fields (e.g., Reuter-Lorenz & Baynes, 1992), they used less stringent tasks with no eye-trackers to ensure fixation accuracy and the word-nonword effect produced by their LVF stimuli was only marginally significant.

#### 7.2.1.2 Chinese

Unlike the consistent findings of LH dominance in research using English or alphabetic languages as stimuli, investigations into the hemispheric asymmetries in visual Chinese character recognition have seen an unresolved dispute over three arguments. The first argument is that the LH dominance in language processing is a universal phenomenon and it applies to Chinese character recognition as well. A second opinion holds that given the apparent differences between English and Chinese, i.e., alphabetic vs pictographic, linear letter strings vs two-dimensional compact square shapes, it is reasonable to assume that Chinese characters are processed as pictures and thus the RH is more involved than the LH. Standing between the first two arguments is a third view which proposes balanced or equivalent role for the two hemispheres in Chinese character recognition.

Specifically, the argument for the LVF/RH dominance in Chinese character perception was proposed earlier than the other two views in the 1970s (Cheng & Yang 1989; Hatta, 1977; Taso & Wu, 1981; Tzeng, Hung, Cotton, and Wang, 1979, etc.). For example, Tzeng et al. (1979) found a LVF superiority for single Chinese character displays. Sasanuma, Itoh, Mori, and Kobayashi (1977) used nonsense Kana (phonetic symbols in Japanese) and Kanji (logographs borrowed from Chinese) as stimuli and observed a significant RVF superiority for recognition of Kana and a nonsignificant trend toward a LVF superiority for Kanji. Subsequently, Hatta (1977), using meaningful

stimuli, found a significant LVF superiority for the recognition of Kanji. Also, using a Stroop task, Tsao & Wu (1981) obtained more Stroop interference when Chinese color characters were presented in the LVF, in contrast to observations with English-speaking subjects. Based on evidence of RH advantage in accessing colour information (e.g., Davidoff, 1976; Pennal, 1977). Tsao & Wu argued that the RH was also the dominant hemisphere for processing Chinese characters and therefore Chinese colour characters and colour information may be competing for the same perceptual capacities in the RH, while this competition may be less among English readers. Using a two-alternative forced choice task, Cheng & Yang (1989) observed the LVF advantage for Chinese characters and a more prominent character superiority effect in the LVF than in the RVF.

As for the 'balanced' view, Rastatter, Scukanec & Grilliot (1989) measured subjects' lexical decision vocal reaction times and RTs to unilaterally presented Chinese characters in the LVF and the RVF and concluded that the two hemispheres were comparable in visually identifying Chinese characters, though they noted that the LH was superior in performing post-access decision processes. Tang, Xu, & Ou (1988) asked participants to name single characters, two-character compound words and Arabic numbers unilaterally presented in either visual field at different exposure durations (100, 50, 20, 10, 5 ms). They found no differences between the two visual fields for any of the three types of stimuli at any of the employed exposure durations and argued that the two hemispheres of Chinese speakers played an equal role in processing these stimuli. Fang (1997) failed to find any visual field effects on character recognition under naming or lexical decision tasks.

Compared to the other two views, the 'RVF/LH dominance' view has seen less evidence from the early behavioral studies. For example, Zhang & Peng (1983)

measured naming accuracy for Chinese characters in adults and school children and found the RVF advantage in both subject groups. Luo & Shui presented Chinese characters and pictures in the LVF/RVF and the central visual field simultaneously and asked participants to decide whether the two characters belonged to the same semantic category. They observed higher judgement accuracy for character stimuli when presented in the RVF and the central visual field and for picture stimuli when presented in the LVF and the central visual field.

It is obvious from the above brief overview that pure behavioral studies in visual Chinese character recognition have yielded inconsistent results. One explanation is that a variety of inappropriate tasks, e.g., naming, lexical decision, stroop task, semantic judgement of bilaterally presented stimuli, alongside with other factors such as stimuli characteristics and stimuli sizes, may have caused the discrepancies in their results. Indeed, some researchers who used different tasks in their studies reported different patterns of hemispheric lateralization. For example, Huang & Jones (1980) used naming and the Reicher-Wheeler task in two separate experiments and reported no significant visual field effects under the naming task and a LVF advantage in terms of discrimination accuracy under the Reicher-Wheeler task. Leong, Wong, Wong, & Hiscock (1985) compared participants' response accuracy to unilaterally presented Chinese characters under three different tasks and found the classic RVF advantage under the phonological matching task and the semantic categorization task while obtaining no differences between the two visual fields under the lexical decision task (though none of these tasks yielded significant visual asymmetries in RT). In a similar vein, Yang & Cheng (1999) employed the same two-alternative forced choice paradigm for three separate experiments while each emphasizing the retrieval of a different aspect of lexical knowledge, orthographic, phonological and semantic. Similarly they also

found the RVF advantage under the phonological and the semantic tasks while obtaining under the orthographic task the LVF advantage for legal characters and a more prominent character superiority effect in the LVF than in the RVF.

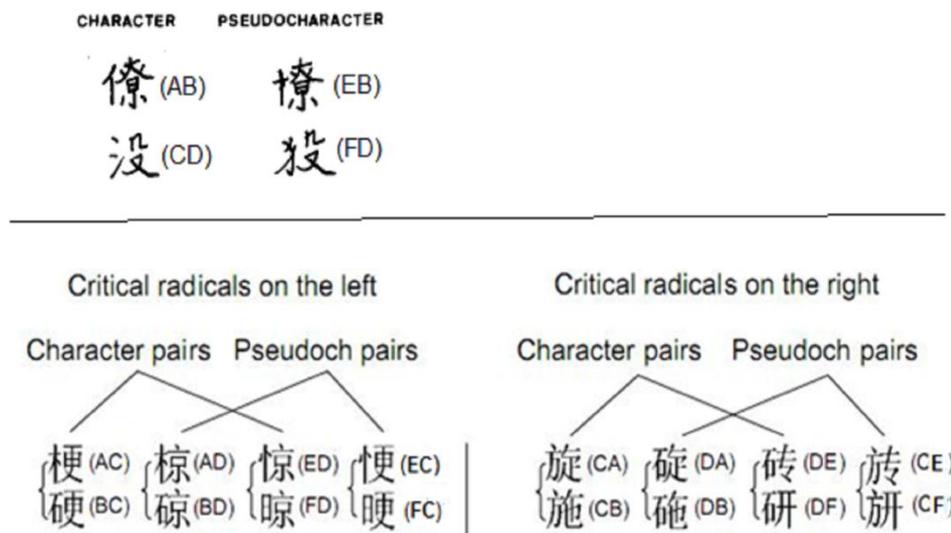


Figure 7.1. Contrasting stimulus structure in Yang & Cheng (1999) and the present experiment. The upper section shows that, in Yang & Cheng (1999), critical radicals B and D were paired with different pairs of radicals (A/C vs E/F) as the remaining content of the stimuli, which may cause the confounding that any differentiated identification accuracy between characters and pseudocharacter was due to difference in physical or linguistic context. In contrast, such confounding was ruled out in the present study by counterbalancing the identity as well as the position of critical radicals across characters and pseudocharacters.

As for the word superiority effect in lateralized Chinese recognition, it is a research question that very few studies have specifically investigated. Non-character stimuli have been typically used in lexical decision tasks and associated with inferior participant performance compared to legal characters when presented laterally. The above-mentioned Yang and Cheng (1999) and their earlier work Cheng & Yang (1989) used two-alternative forced choice paradigm. However, in these two studies, the two alternatives in a character or pseudocharacter pair differed by both of their constituent radicals. As shown in the upper section of Figure 7.1, critical radicals B and D were paired with different pairs of radicals (A/C vs E/F) as the remaining content of the

stimuli under the character and the pseudocharacter conditions, which resulted in distinct physical context for the critical radicals across conditions. Consequently, this can cause the confounding that whether any differential discrimination accuracy for the same critical radicals across conditions was due to difference in the physical or linguistic context in which they occurred. In contrast, such confounding was ruled out by counterbalancing the identity as well as the position of critical radicals across characters and pseudocharacters.

## 7.2.2 An overview of neurophysiological studies investigating hemispheric asymmetry and the word superiority effect in word recognition

### 7.2.2.1 English

Various neurophysiological techniques have been used to study how the the human brain processes verbal stimuli including EEG, MEG, PET, and fMRI. Compared to the conventional psychophysical studies in which conclusions about hemispheric lateralization pattern are based on how participants respond to stimuli presented in the two hemifields, these neurophysiological techniques provide more straightforward information about hemispheric activities and thus have been combined with both central and hemifield presentation (e.g., Itzhak, Babkoff, & Faust, 2007; Nelson, Collins, & Torres, 1990). As in psychophysical studies, the typical left-lateralized asymmetry has been consistently reported in the neurophysiological investigations using English, although there is evidence that factors like task, stimuli context and stimulus presentation time affect the extent of the LH dominance and in some cases even result in a reversed lateralization pattern (e.g., Bentin et al., 1999; Mercure et al., 2008; Proverbio & Adorni, 2009; Spironelli & Angrilli, 2006; Spironelli & Angrilli, 2009). Although this LH dominance has been observed at various times of brain processing as reflected in several ERP components, its earliest manifestation was found during the N1

time window in most of previous studies..

Notably, the N1 time window is also where the earliest ERP differences between words and word-like stimuli (pseudowords, consonant strings, etc.) were most commonly identified. In most studies where such context effects were found in the N1, words showed greater negativity than other verbal stimuli, though there are occasional studies with opposite results. In addition, the existing literature has identified an area in the occipito-temporal region of the LH, probably centered on the left fusiform gyrus, as responsible for the activations during the N1 time window (~150-200 ms) and this finding is consistent across experimental tasks and brain mapping techniques (fMRI, MEG and EEG-based source localization).

Indeed, apart from a few fMRI studies which detected stronger signals in the LH, the only ERP study that reported pre-N1 hemispheric lateralization when reading English words, to the author's knowledge, is Mercure et al. (2008). Inconsistent with the typical finding of LH dominance in English word recognition literature, they found right-lateralized asymmetry in terms of greater amplitudes in the RH for both word and face stimuli at P1 latency (peaking at ~100 ms) irrespective of exposure durations. Using French words and nonwords as stimuli, Cohen, Dehaene, & Naccache, Lehéricy, Dehaene-Lambertz, Henaff, and Michel (2000) also revealed hemispheric lateralization at P1 (peaking at ~136 ms for LVF stimuli and at ~120 ms for RVF stimuli) with greater P1 activations over left electrodes irrespective of the stimulated hemifield.

Similarly, only a few ERP studies involving words versus pseudowords or nonwords have reported stimulus type modulations before the N1. Coch & Mitra (2010) employed a masking Reicher-Wheeler task and found that nonwords elicited the strongest P1 responses followed by word, pseudoword and letter-in-x's stimuli with no difference between the latter three. They attributed the nonword vs word difference to

some orthographic regularity and familiarity effects. However, this account is questionable as it cannot explain why an unpronounceable string of single letter and three xs (the letter-in-xs condition) is necessarily closer to the original matched word in terms of orthographic regularity and familiarity than an unpronounceable string of four letters.

Three other studies used the lexical decision task and observed stimulus type modulations on P1 amplitude in opposite patterns. Specifically, Segalowitz and Zheng (2009) found words activated greater P1 than nonwords whereas Hauk, Patterson, Woollams, Watling, Pulvermüller, & Rogers (2006b) and Sereno et al. (1998) reported weaker P1 activity for words compared to pseudowords and/or consonant strings. These studies also disagreed on their interpretations of the nature of the word-pseudoword/nonword difference in the P1. Segalowitz and Zheng (2009) and Sereno et al. (1998) argued that it reflected very early lexical activations while Hauk et al. believed it was due to certain typicality effect. Segalowitz & Zheng (2009) and Hauk et al. (2006b) had only words and nonwords/pseudowords without any benchmark condition and Sereno et al. (1998) used nonwords as the benchmark condition. Having no benchmark condition or using one not visually matched to the word condition can result in limitations in determining whether any differences between words and pseudowords reflect genuine lexical effect or are just due to some low-level visual processing which also caused word length effect in other studies. Specifically, as mentioned earlier, early exogenous ERPs like the C1 and the P1 are especially sensitive to variations in the physical characteristics of stimuli including shape, size and spatial frequency. It has been shown in the literature that the P1 can not only differentiate between stimuli from different categories (such as faces and words, e.g., Rossion et al., 2003) but also between stimuli from the same category when they show distinct

physical features (such as words with varied length, e.g., Hauk et al., 2006b). The most notable difference between words versus pseudowords and nonwords in terms of physical characteristics is that words have familiar coarse-scale information including the overall outline and supra-letter features whereas pseudowords and nonwords do not. Therefore, the inclusion of a benchmark condition which is visually matched to words at the level of coarse-scale spatial frequency will be especially useful in determining the nature of any P1 amplitude difference between words and pseudowords. If the P1 amplitude differed between the word and pseudoword conditions while similar level of P1 response was obtained for the word and the visually-matched benchmark conditions, this may indicate that the visual system at this early stage is mainly responding to physical characteristics of stimuli without fully establishing their lexical status.

Hemispheric asymmetry and context effects after the N1, whether as in their initial instances or further manifestations, have been reported in the P3 and the N400. Unlike the robust left-lateralized scalp distribution found in the N1, topographic patterns for the P3 and the N400 in different studies were not always in agreement. In those studies which reported hemispheric lateralization, most showed a right-lateralized topography while some found the opposite. These mixed results in ERP surface recordings are, however, accompanied by the more consistent findings in localizing the source generators responsible for the P3 and the N400. MEG, fMRI and intracranial ERP studies have all identified sources in the LH for the two components. In some studies, surface recordings showed greater cortical response over the RH sites whereas source localization suggested that the LH was more active. Researchers have used 'paradoxical lateralization' to explain the contradiction. In this particular case it refers to the fact that a LH generator affects right-hemisphere electrodes due to fissural morphology and conductance properties (e.g. Lau, Phillips, & Poeppel, 2008).

Investigations of context effects have led to different results for the P3 and the N400. Specifically, words are generally reported to elicit greater activations than other verbal stimuli in the N400 with occasional exceptions whereas there has been similar amount of evidence for either way in the P3.

#### 7.2.2.2 Chinese

Neurophysiological techniques were first applied to investigations of Chinese character recognition in the early 1990s (e.g., Valdes-Sosa, Gonzales, Liu, Zhang, Hou, & Bobes, 1993). There are two distinctive features about neurophysiological research in Chinese hemispheric lateralization. Firstly, compared to research using English as stimuli which see a more balanced division between ERP and fMRI studies, neurophysiological research in Chinese hemispheric lateralization is mainly composed of fMRI studies. Secondly, unlike fMRI studies in English reading that have almost uniformly reported a strong left-lateralized neural network. fMRI studies in Chinese hemispheric lateralization have generally observed distinct lateralization patterns in different brain areas. Specifically, left-lateralized activations are typically found in the temporal (mainly involving the left middle and posterior fusiform and temporal gyri, BA 37/19) and the frontal (mainly involving the left inferior frontal gyrus, BA 47) cortices while the occipito-parietal cortices often feature either no asymmetries or a right lateralization (e.g., Dong, Nakamura, Okada, Hanakawa, Fukuyama, Mazziotta, & Shibasaki, 2005; Kao, Chen, & Chen, 2010; Nakamura, Oga, Okada, Sadato, Takayama, Wydell, Yonekura, & Fukuyama, 2005; Tan, Spinks, Gao, Liu, Perfetti, Xiong, Stofer, Pu, Liu, & Fox, 2000; Xue, Dong, Chen, Jin, Chen, Zeng, & Reiman, 2005; Zhang, Tang, Ma, Weng, Li, & Jia, 2001). There is also MEG evidence for such area-specific lateralization patterns (e.g., Lin, Liao, Chen, Yeh, Shih, Wu, & Ho, 2006). Typical experiment tasks include (silent) naming, phonological matching or judgement (with

bilateral presentation), lexical decision. Tan et al. (2000) even used a character generation task. In the respect of ERP studies, the N400 is typically associated with enhanced activations in the RH (e.g., Hsiao, Shillcock, & Lee, 2007; Valdes-Sosa et al., 1993). Among the few studies that reported pre-N400 hemispheric asymmetries, Hsiao, Shillcock, & Lee (2007) reported RH lateralization at the P1 peak latency with silent naming task; He, Yin, Luo, & Weekes (2006) asked participants to judge the orthographic similarity of bilaterally presented characters and found right-lateralized N1 activities.

Regarding the neural correlates of context effects in Chinese character processing, no study in the existing literature has used the Reicher-Wheeler task to investigate the cortical differences between legal characters and other character-like visual constructs. Indeed, many researchers have chosen a judgement task under which participants decided whether the two simultaneously or sequentially presented characters were orthographically, phonologically, semantically, or dimensionally identical or related without comparing between characters and character-like stimuli (e.g., Liu et al., 2003; Kao et al., 2010; Zhang et al., 2009). Among the few studies which compared brain responses to characters and character-like stimuli, Wang, Li, Zhang, Tu, Yu, and Qiu (2010) used a passive viewing task and reported the earliest ERP modulations of character-ness with pseudocharacters eliciting a greater positivity between 200--250 ms and a greater negativity between 350-450 ms than characters over the posterior area. There is also fMRI evidence for differential activations between characters and other character-like stimuli in the left or bilateral fusiform gyri (e.g., Kao et al., 2010; Liu, Zhang, Tang, Mai, Chen, Tardif, & Luo, 2008). Liu et al. (2008) also observed consistent activations in the left middle frontal gyrus (BA9) for characters and pseudocharacters in contrast to artificial characters (random combination of incomplete

radicals).

### 7.2.3 Dispute between the `unilateral' and the `bilateral' projection views

As mentioned earlier, researchers have commonly used either central (only in neurophysiological studies) or lateral display to investigate hemispheric asymmetry in word recognition. When stimuli presented laterally, most studies maintained one single extrafoveal location. In the rare cases where eccentricity was varied, they were usually all outside the fovea (e.g., Busch, Debener, Kranczioch, Engel, & Herrmann, 2004; Kao et al., 2010; Melmoth, & Rovamo, 2003). Lateralized display of words and other verbal stimuli within the fovea has received little attention until recently when series of studies have been conducted centering on the argument of whether the human fovea is precisely split along a vertical midline and accordingly hemispheric asymmetries affect word recognition right up to the point of fixation. Specifically, there is the split fovea theory (also referred to as the `unilateral projection' view by some researchers) which argues that the entire human retina, including the fovea area, is vertically divided into two halves and visual stimuli presented to one side of the fixation point exclusively project to the contralateral hemisphere (e.g., Lavidor, Ellis, Shillcock, & Bland, 2001; Lavidor, Hayes, Shillcock, & Ellis, 2004). Although advocates of the split fovea theory argue that their view is supported by anatomical evidence (e.g., Leff, 2004), the issue is far from resolved and many studies indicate no precise foveal split in hemispheric processing and, indeed, that a substantial area of overlap (typically, 1--3 ° wide) exists around the point of fixation within which information projects to both hemispheres (e.g., Brandt et al., 2000; Bunt and Minckler, 1977; Fendrich et al., 1996; Gazzaniga, 2000; Leventhal et al., 1988; Lindell and Nicholls, 2003; Reinhard & Trauzettel-Klosinski, 2003; Stone, 1966; Stone et al., 1973; Trauzettel-Klosinski & Reinhard, 1998).

Proponents of the split fovea theory attempted to reveal evidence of split-foveal

effects on word recognition by drawing upon the well-established hemispheric specialization in language processing. By presenting words that straddle the point of fixation or varying the number of letters presented on either side of fixation, proponents of the split fovea theory reported that lexical decisions were affected by word length (defined as number of letters) variations to the left of fixation but not to the right and also by the precise location at which a word is fixated to the effect that better performance was observed when the word shown entirely to the right of fixation compared to when entirely shown to the left. For example, Lavidor et al. (2001) manipulated word length in either visual field by presenting five-letter or eight-letter words with the initial two letters to the left of the fixation point or the final two letters to right of the fixation, namely, three letters in either visual field for five-letter words and six for eight-letter words. They found that lexical decision time and accuracy were significantly impaired when three letters were presented in the LVF than when five letters in the LVF but no such differences were obtained in the RVF. The authors argued that their finding can be explained by cerebral asymmetry that the LH is more specialized in language processing and can analyze different number of letters with equal efficiency and therefore supports the split fovea theory. Besides, several ERP studies were conducted in pursuit of electrophysiological evidence of split fovea processing in word recognition (e.g., Martin, Thierry, Démonet, Roberts, Nazir, 2007.). Motivated by the findings with post-callosotomy epileptic patients that visual information is transferred from one visual cortex to its contralateral homologue via the splenium of the corpus callosum, these studies compared the P1 peak latencies recorded on homologous sites in the two hemispheres and reported that the P1 activities in the hemisphere ipsilateral to the stimulated visual field peaked later than those in the contralateral hemisphere when letter strings were fixated at the first or last letter

(i.e., when all but the fixated letter were displayed in one visual hemifield only). Advocates of the split fovea theory argued that this delay in the P1 latency reflected interhemispheric transfer of information which resulted from unilateral projection.

However, the validity and credibility of these findings is questionable in several aspects, including using large stimuli extending way into the extrafoveal vision (e.g., 6.65° of horizontal visual angle as used in ) and relying on merely instructing participants to fixate accurately rather than monitoring participants' fixations (e.g., by using an eye-tracker) to ensure that the required fixations actually occurred (see Jordan & Paterson, 2010 for a most recent review). Using stimuli exceeding the fovea to seek evidence for split foveal processing in word recognition is inappropriate. Furthermore, decades of research has indicated that participants have difficulty monitoring and controlling their eye movement behaviour when attempting to fixate a particular location and merely instructing participants to fixate accurately is ineffective and produces substantial errors in fixation location (see Jordan et al., 1998; Gazzaniga, 2000). Most importantly, Jordan and colleagues re-evaluated the claims of Lavidor et al. (2001) over a series of experiments under different viewing conditions with stimuli presented in a range of sizes, including using its original stimuli and procedures (Jordan, Paterson, and Stachurski, 2009; Jordan, Paterson, Kurtev, and Xu, 2010). None of these experiments has been able to replicate the findings of Lavidor et al. (2001) or provide evidence for a functional division in hemispheric processing at the point of fixation.

Recall that it was introduced earlier that two common types of left-right structured Chinese characters are the SP and PS characters with the former consisting a semantic radical on the left and a phonetic radical on the right and the latter showing the reversed order. Proponents of the split fovea theory also conducted similar behavioural and ERP studies using the SP and PS Chinese characters as stimuli (Hsiao & Shillcock,

2005; Hsiao et al., 2007). These studies reported that the structure of centrally fixated characters (i.e., the positioning of the two radicals, whether SP or PS) had an impact on participants' responses. Hsiao & Shillcock (2005) asked participants to name `centrally fixated SP and PS characters and found that males responded significantly faster when the phonetic information was on the right, whereas females showed a non-significant tendency in the opposite direction. They argued that it was due to split-foveal processing so that the two radicals in a centrally fixated SP or PS character were initially projected to and processed in different (contralateral) hemispheres. In pursuit of neurophysiological evidence of split-foveal character processing, Hsiao, Shillcock, & Lee (2007) recorded participants' ERP responses while they silently named centrally-fixated SP and PS characters and observed that SP characters elicited larger N1 compared with PS characters in the left hemisphere, whereas the right hemisphere had the opposite pattern. Also, using repetitive transcranial magnetic stimulation (rTMS) and centrally fixated" SP characters, Hsiao, Shillcock, & Lavidor (2006) examined semantic radical combinability effects in a semantic judgment task and showed that rTMS over the left occipital cortex impaired the facilitation of semantic radicals with large combinability whereas right occipital rTMS did not. This impairment of combinability effect in the left hemisphere was again attributed to the split-foveal assumption that the phonetic radical in a `centrally fixated' SP character initially projected to the left hemisphere and when the semantic radical had large combinability, the phonetic radical was more informative in determining the identity of the whole character and thus determining whether the meaning of the semantic radical was related to that of the entire character.

Although Hsiao and colleagues (2005, 2007) used within-fovea stimuli, they did not ensure that two radicals of SP/PS characters were each projected to the contralateral

hemisphere only. Apart from the ultimate failure to use an eye-tracker to monitor participants' actual fixations, neat and exclusive unilateral projection of either radical to the contralateral hemisphere may have been prevented due to some natural features of Chinese character orthography. Two of such critical features were mentioned earlier in Section 2.1.2. Firstly, 'left-right structured' is rather a simplified term to roughly describe how the two component radicals adhere to each other in this case and by no means equals the pure linear structure of English words. In fact, the two radicals often closely interact with each other in a way that the strokes of either radical extend into the blank space of the other to make the character an integrated whole. As a result, SP/PS characters rarely have a vertical gap running undisrupted between the two radicals as inter-letter spaces in English words. To add to the complexity, the component radicals in a compound character (however structured, left-right, left-middle-right, top-down, or closed, etc.) are rarely equally sized. Specifically, in a SP or PS character, it is usually the phonetic radical that outsizes the semantic radical with greater width and equal or greater height. Consequently, the boundaries between the two radicals is typically to the left of the vertical midline in a SP character and to the right in a PS character. Hsiao and colleagues described their stimuli as 'centrally fixated' and did not mention that the SP/PS characters used in their studies had been modified as to remove the natural intermingling and the proportional sizing of the two radicals. Within the split fovea context, this means that the left half of a SP character, including the semantic radical and part of the phonetic radical, projected to the RH and the right half, i.e., the remaining part of the phonetic radical, to the LH, and the other way around in a PS character.

In summary, the credibility of studies advocating split fovea theory is greatly undermined by not ensuring accurate fixation which is fundamental when investigating

how foveal information projects to the visual cortex. When Chinese characters are used as stimuli, an additional issue is that the natural Chinese orthography makes it hardly possible for either radical in a SP/PS character to exclusively project in its entirety to the contralateral hemisphere. The existing studies using Chinese stimuli to study foveal processing neither ensured accurate fixation nor overcame characters' orthographic constraints.

#### 7.2.4 Aims and hypotheses of the present study

This chapter describes an experiment combining behavioral and ERP measures in which the following aspects of Chinese character recognition were investigated. First of all, the experiment aimed to determine if there exists behavioral and/or ERP evidence of context effects in lateral Chinese character recognition by comparing participants' responses to character, pseudocharacter and VM stimuli, namely, if the context in which the visual contents of a character occurs affects participants' behavioral and/or ERP response as to result in the character superiority over pseudocharacters and VMs as well as pseudocharacter superiority over VMs. Secondly, it examined if the two hemispheres show any pattern of asymmetry or lateralization when processing Chinese characters and furthermore if the same pattern appears for both foveally and extrafoveally presented characters by presenting stimuli at 0.15 and 2.0 degrees in either visual field. Thirdly, the experiment attempted to provide estimations on a spatiotemporal profile of cortical character processing based on findings from the first two questions, e.g., the points of time when the brain areas where ERP responses differ between stimulus types, visual fields, and hemispheres.

The hypotheses were as follows. The character superiority over pseudocharacters obtained in the preceding experiment, together with the word superiority over pseudowords previously reported in the literature, all provided support

for the argument that orthographic processing occurs in an outside-in fashion and the coarse-scale configurational information in a character or word (including the overall outline and the spatial interactions between its component elements) has important benefits for the discrimination of its identity. Furthermore, the importance of 'outside' information as contained in exterior letters (beginning and ending letters) in a word has been shown in both central and lateralized display (e.g., McCusker, Gough, & Bias, 1981; Humphreys, Evett, & Quinlan, 1990; Jordan et al., 2000). It was therefore hypothesized that lateralized character processing also occurred in a similar coarse-to-fine manner as in central presentation. If the two hemispheres were overall equally involved throughout this coarse-to-fine processing, characters should be identified with similar levels of accuracy in either visual field and a character superiority over pseudocharacters should be observed in either visual field, too. If one hemisphere was more involved than the other throughout each stage of character processing, characters presented extrafoveally in its contralateral visual field should be identified more accurately than those presented extrafoveally in its ipsilateral visual field. If there did exist a division within the fovea and one hemisphere played a more important role than the other throughout character processing, the same visual field difference should be observed for foveally presented characters as for extrafoveally presented ones; otherwise if foveal input initially projected to both hemispheres or the two hemispheres were overall symmetrical in their capacities of character processing, visual field should not affect identification accuracy for characters presented within the fovea.

## 7.3 Methodology

### 7.3.1 Participants

Sixteen paid participants (8 males and 8 females, aged 19-26) took part in the

experiment. All were right-handed (determined by a revised Annett Handedness Questionnaire (Annett, 1970)) native speakers of Chinese, reported normal or corrected to normal vision and were screened using a Bailey-Lovie eye chart for minimum binocular acuity of 3/3 or better. Among the sixteen participants, three participants' EEG recording was disrupted by a bridging problem over the parieto-occipital area and an additional five participants' EEG data was severely contaminated by blinks, eye movements and other sources of transient noise (see the Methodology section for details of artefact rejection)<sup>4</sup>. Therefore, only eight (4 males and 4 females, response hand counter-balanced) participants were included in the ERP analyses.

### 7.3.2 Stimuli

Twenty-four sets of matched pairs of characters, pseudocharacters and fragmented visual matches of characters were selected from the stimuli used for Experiment 2. Half of these sets had the critical radicals all on the left and the other half on the right (see characters, pseudocharacters and VMs listed in Appendices 1 and 2). The character pairs from another twenty-four sets in the same stimuli pool were also included in this experiment as a filler condition to counterbalance the overall number of lexical and non-lexical items. The purpose of this was to rule out any possible bias in response caused by participants viewing non-lexical items more often than lexical items. Therefore, there were four stimulus conditions in this experiment, i.e., characters, pseudocharacters, fragmented visual matches of characters and filler characters, each containing 96 items. Only the first three stimulus conditions were submitted to statistical analyses.

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<sup>4</sup> A standard procedure in preparation for an EEG session is to use a gel or paste electrolyte to create electrical conductivity between the scalp and electrodes. When the electrolyte spreads beyond the containment of an electrode as to connect to its neighbouring electrodes, bridging is caused and recording at the bridged electrodes will show the same (not true) EEG signal.

As explained earlier, the width of stimuli varied to make the radicals in pseudocharacters look as natural as possible while the average widths of characters and pseudocharacters were kept the same within each set of matched pairs. Viewed from a distance of 85 cm, the widest among these stimuli images from Experiment 2 subtended a horizontal visual angle of approximately 1.5 degrees and the narrowest 1 degree<sup>5</sup>. These original stimuli images were used for extrafovea presentations. In order to match the visual acuity of stimuli at the two eccentricities, stimulus size scaling was performed for foveal presentations by reducing the extrafoveal presentations to half of their original sizes (see e.g., Farrell & Desmarais, 1990; Slotnick, 2001). Accordingly, the widest foveal stimulus subtended 0.75 degrees and the narrowest 0.5 degrees.

### 7.3.3 Stimuli presentation apparatus

The experiment was conducted in a sound-attenuated and darkened room. All stimuli were presented on a gamma-corrected high-definition 21 inch ViewSonic G220F display monitor. A Cambridge Research Systems VSG 2/5 card controlled stimulus presentation, timing and generation of EEG signal triggering. Responses were collected via a Cambridge Research Systems CT3 button box. A chin-rest was used to ensure a constant viewing distance of 85 cm at all times. Fixation was monitored by using a head-mounted Skalar IRIS eye-tracking system (Cambridge Research Systems) which was clamped in a head brace to prevent head movement throughout experiment sessions. This arrangement allowed accurate and consistent measurement of the horizontal fixation location. The output of the tracker was recorded through the ADC input of the Cambridge Research Systems VSG2/5 card, which also controlled the visual display (see Jordan et al., 1998; 2000).

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<sup>5</sup> Stimulus image width was measured in the following way. First, pixel size was calculated by dividing the width of the monitor (in cm) by horizontal resolution of the monitor (in number of pixels). Second, width (in cm) was determined for each stimulus image by multiplying the number of pixels along its horizontal midline by pixel size.

### 7.3.4 Design

There were three stimulus manipulations, namely, stimulus type (character, pseudocharacter, and VM), visual field (LVF and RVF), and eccentricity (fovea and extrafovea), which made a 3 x 2 x 2 factorial design for behavioural data analysis. Each stimulus was shown once in each of the 4 locations along the horizontal midline of the screen, i.e., left visual field extrafovea (LX), left visual field fovea (LF), right visual field fovea (RF) and right visual field extrafovea (RX). This resulted in 12 possible combinations of stimulus type and stimulus location, i.e., LX-presented characters (LX\_Ch), LX-presented pseudocharacters (LX\_Ps), LX-presented visual matches (LX\_VM), LF-presented characters (LF\_Ch), LF-presented pseudocharacters (LF\_Ps), LF-presented visual matches (LF\_VM), RF-presented characters (RF\_Ch), RF-presented pseudocharacters (RF\_Ps), RF-presented visual matches (RF\_VM), RX-presented characters (RX\_Ch), RX-presented pseudocharacters (RX\_Ps), and finally RX-presented visual matches (RX\_VM).

The inner-edge eccentricities from central fixation for fovea and extrafovea presentation were 0.15 degrees and 2 degrees respectively. It was mentioned in Section 7.3.2 that there were 96 items under each stimulus condition. Besides, 96 filler characters were also shown to counterbalance the overall number of lexical and nonlexical trials, though not included in data analysis. Therefore, each participant was shown a total of 1536 (96 items under each stimulus type, 3 stimulus types and 1 filler type, and 4 locations) test trials. The sequence of these 1536 trials was randomized differently for each participant and then broken into 5 sessions. Each session contained 308 experimental trials (with the exception of Session 5 containing 307) and lasted approximately 15 minutes. When central display is used, it is common practice in a Reicher-Wheeler paradigm to present the two alternatives one above the other around

the central fixation in the same size as used for target display, as in Experiments 2, 3, and 4 in this thesis. However, this experiment did not aim to investigate whether showing alternatives in the four screen locations (LX, LF, RF, RX) and the two sizes (extrafoveal targets twice as large as their foveal counterparts) particularly used for target presentation would affect participants' responses. More importantly, it should not cause any confounding in this respect. Therefore, an intermediate size between foveal and extrafoveal sizes and a semi-random screen location were used to present alternative choices. Specifically, when an item was presented as an alternative choice, it was 1.5 times as large as when it was presented as a target in the fovea. Besides, a point along the horizontal midline of the screen was semi-randomly generated as the centre point for each pair of alternatives. The criterion for semi-randomization was that the eccentricity of this point was constrained within 10 degrees on either side of fixation. The reason of this semi-randomization was two-fold. Firstly, it avoided the possibility of post-target perception causing biased responses to targets, which may occur when alternatives were presented along the same vertical line as their targets or in the centre of the screen. Secondly, the 10-degree eccentricity restriction ensured that alternatives were not perceived outside the parafovea where visual acuity is significantly poorer. The position of the correct alternative choice, whether shown as the top or bottom display, was randomized and the hand used to produce responses was counterbalanced across participants.

Additional independent (e.g., hemisphere, electrode) and dependent variables (e.g., latency, amplitude) applied to ERP data analysis with variations from step to step, which will be detailed in due places in Section 7.4.2.

### 7.3.5 Procedure

Participants were given both written and oral instructions which explained the

Reicher-Wheeler task and emphasized the importance of accurate fixation. Experiment procedure along the time line is shown in Figure 7.2. At the start of each trial, a fixation dot appeared at the centre of the screen. Participants were required to fixate this point and stimulus presentation was prevented until accurate fixation occurred continuously for 300 ms. If fixation deviated from the fixation point before the presentation of the word, stimulus presentation was immediately prevented and continued to be prevented until accurate fixation again occurred for at least 300 ms (see Patching & Jordan, 1998, for further details of this procedure). When this criterion was satisfied, a target was shown for 17 ms in its designated location, i.e., at 0.15 or 2 degrees eccentricity in the LVF or the RVF (LX, LF, RF or RX, see Figure 7.2, Panel B for an illustration of target positions), which was followed by a blank screen for 483 ms. The two alternatives appeared 500 ms post-stimulus onset in a semi-randomly selected location within 10 degree eccentricity along the horizontal midline. Participants had a response period of 1500 ms starting from alternative onset to make a choice by using his or her designated hand. The alternatives were removed after a response within this period or after the time-out of this period. The next trial commenced 1000ms after removal of alternatives. The fixation dot was held on the screen throughout each session to avoid any visual artefacts in the EEG signal caused by its repeated appearance and disappearance. Participants had a 5-10 min break in between the sessions.

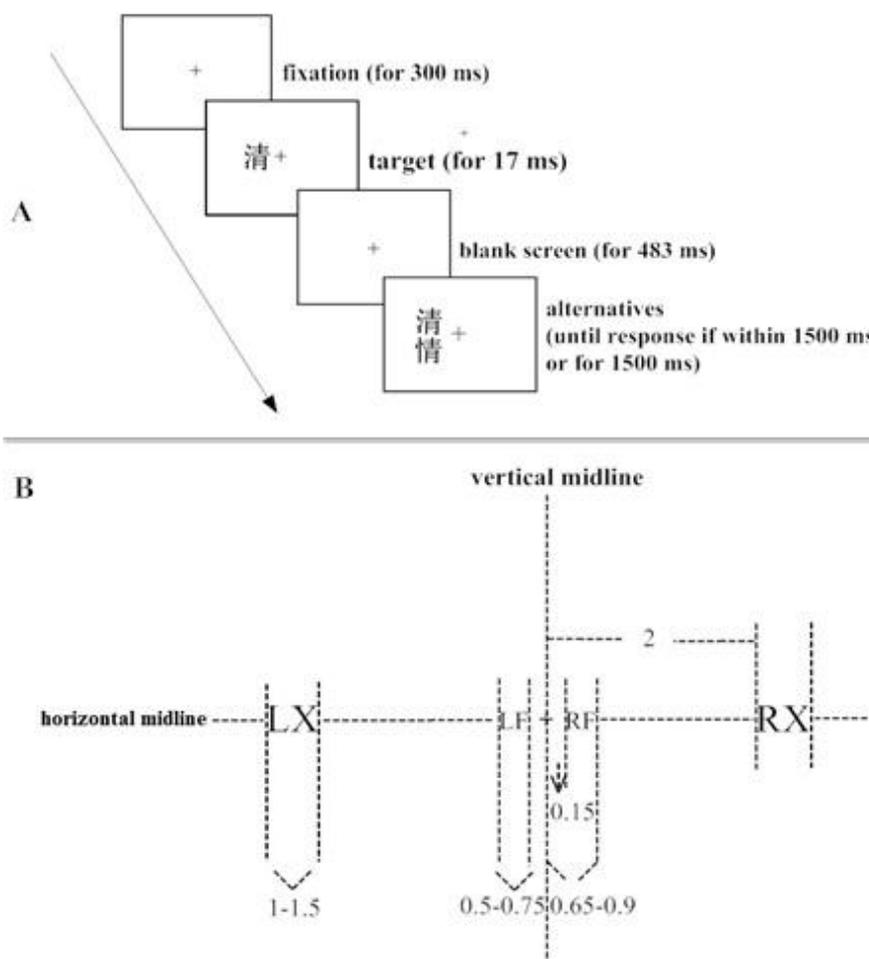


Figure 7.2. Trial procedure of Experiment 5 and screen locations for target presentation. Panel A illustrates the procedure of each trial in Experiment 5. This is only a schematic diagram summarizing step-by-step procedure on each trial and specific screen locations for target presentation is detailed in Panel B. There were four possible screen locations for target presentation, LX, LF, RF and RX. Each target was randomly assigned one of these four locations. All numbers in Panel B are in degree, depicting stimulus sizes and eccentricities. Dotted lines did not appear in the experiment and are for reference only.

### 7.3.6 EEG data recording and pre-processing

Continuous 32-channel EEG and EOG was recorded via a Waveguard elastic cap containing 64 unshielded and sintered Ag-AgCl electrodes (CAP-ANTWG64; ANT, Netherlands) in the international 10-5 montage, as shown in Figure 7.3 and a DC 32-channel amplifier (1-kHz sampling rate; 250 Hz high cutoff frequency; Brain Products, Inc, Germany). EEG signal was referenced on-line to the right-earlobe electrode and

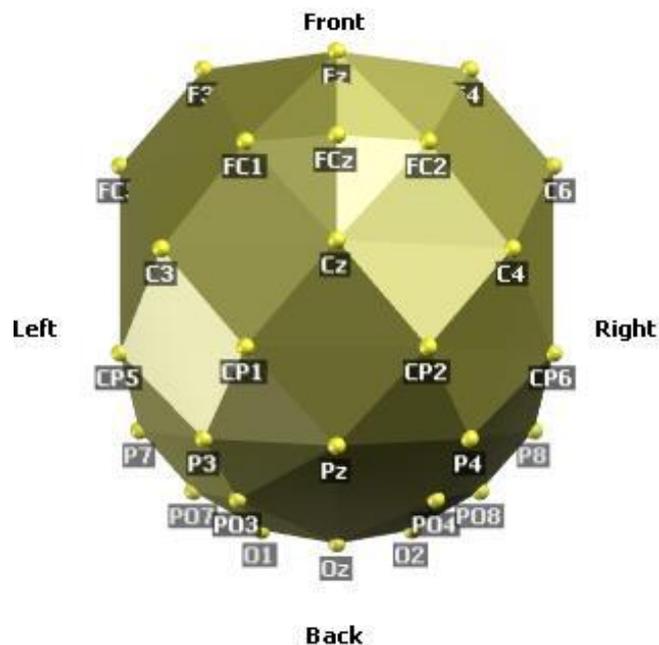


Figure 7.3. Electrode montage in Experiment 5

then re-referenced offline to the average of the right- and the left-earlobe electrodes. HEOG (horizontal electrooculogram) was recorded via two electrodes placed in a bipolar montage at approximately 1 cm from the outer canthi of both eyes. VEOG (vertical electrooculogram) and blinks were recorded via an electrode positioned below the right eye and referenced to the right earlobe. Impedances were maintained below 5k $\Omega$ . A notch filter (50 Hz) was used for all recorded channels. Only EEG data for trials with correct responses were kept for pre-processing and later analyses. Epochs from 100 ms pre-stimulus to 500 ms post-stimulus onset were averaged for each of the stimulus condition in each of the locations (12 combinations in total) and from each participant to calculate the ERPs. In addition to the application of an automated artifact criterion of  $\pm 30$   $\mu\text{V}$  at HEOG sites and  $\pm 80$   $\mu\text{V}$  at all the other sites, the data were visually inspected to reject epochs with blinks, eye movements, muscle movements or other sources of transient noise. Baseline was defined as the 100 ms pre-stimulus period. Averaged ERPs were bandpass filtered (1-30 Hz) to further remove slow and sustained

shifts in voltage of non-neural origin during data acquisition and to reduce high-frequency noise.

### 7.3.7 ERP analyses

#### 7.3.7.1 Peak analyses

Visual inspection of the ERP data over the entire scalp distribution found four major peaks common to all 12 experimental conditions, i.e., P1, N1, P2 and P3, which manifested two latencies depending on the stimulated visual field and the hemisphere of response recording. P1 and N1 were most prominent in the lateral parieto-occipital area, the P2 along the fronto-centro-parietal midline, and finally P3 in the parietal area. Three pairs of homologous electrodes were selected for each of these four peaks in the scalp area where they manifested maximum brain activities. Specifically, O1\_O2, PO7\_PO8 and P7\_P8 were selected for the peak analyses of the P1 and the N1, FC1\_FC2, C3\_C4 and CP1\_CP2 for the P2, and PO3\_PO4, P3\_P4 and P7\_P8 for the P3. The odd numbers in electrodes labels (e.g., 1, 3, 7) denotes a LH origin and the even numbers (e.g., 2, 4, 8) denotes a RH origin. Peak analyses were performed in BrainVision Analyzer 2.0 (Brain products, Munich, Germany). Peak latencies and amplitudes were detected in a semi-manual manner and then subjected to separate 4-way (Eccentricity\*VisField\*Hemisphere\*Stimulus) repeated measures ANOVAs for each selected pair of electrodes for a particular peak.

#### 7.3.7.2 Waveform point-wise t-tests

Traditional peak analysis applies to only a limited number of electrode sites over a certain scalp area during a more constrained time window whereas ERP waveform t tests provide a macro view of waveform modulations over the entire scalp along the whole ERP epoch. This procedure fills the gaps where traditional peak analysis fails

mainly in two aspects. Firstly, peak analysis only determines whether the peak strength of an ERP component is modulated by any experimental manipulation. In contrast, the ERP point-wise *t* tests depict a more comprehensive temporal profile of ERP differences, most importantly the earliest point of time when the waveform responds differentially to two experimental conditions. Secondly, point-wise waveform *t*-tests are especially useful in comparing the patterns of ERP response when no peaks are available for peak analysis, for example before the first major ERP occurs or over a less-responsive cortical area during the time window of an ERP.

Waveform *t*-tests and the following three steps of analyses were performed using the Cartool software by Denis Brunet (<http://brainmapping.unige.ch/cartool.htm>). Together these multi-step analyses are referred to by Murray and colleagues as the 'electrical neuroimaging' procedure (Murray, Brunet, & Michel, 2008; Murray, Michel, Peralta, Ortigue, Brunet, Andino, & Schnider, 2004; Ortigue, Michel, Murray, Mohr, Carbonnel, & Landis, 2004)

Point-wise paired *t* tests were conducted to determine the timing of differences in ERP responses to different stimuli in each location. (LX\_Ch vs LX\_Ps; LX\_Ch vs LX\_VM; LX\_Ps vs LX\_VM and so on). A temporal criterion of 10 consecutive data points was applied. Specifically, for each electrode, the first time point where the *t* test exceeded the 0.05 alpha criterion for at least 10 consecutive data points (>10 ms at a 1000 Hz digitalization rate) was labeled as onset of an ERP modulation.

#### 7.3.7.3 Global field strength *t*-tests

Waveform point-wise paired *t* tests identify any local strength modulation by examining each individual electrode site. Changes in electric field strength were further analyzed by calculating the global field power (GFP; Lehmann and Skrandies, 1980) from each subject and for each stimulus condition in each location. GFP is equivalent to

the spatial standard deviation of the scalp electric field, yields larger values for stronger electric fields, and is computed as the square root of the mean of the squared value recorded at each electrode (vs. the average reference). As with the ERP waveform data, the GFP data underwent a series of point-wise paired t tests with the same 10 ms temporal criterion. It is important to note that the observation of a GFP modulation does not exclude the possibility of a contemporaneous change in the electric field topography. Nor does it rule out the possibility of topographic modulations (modulations in topographic distribution) that nonetheless yield statistically indistinguishable GFP values. However, the observation of a GFP modulation in the absence of a topographic modulation would be indicative of amplitude modulation of statistically indistinguishable generators across experimental conditions (Murray, Michel, Peralta, Ortigue, Brunet, Andino, & Schnider 2004; Laufer, Negishi, & Constable, 2009).

#### 7.3.7.4 TANOVAs

To statistically identify periods of topographic modulation, global dissimilarity (Lehmann and Skrandies, 1980) between responses to different stimulus condition in each location for each time point per participant was computed using a Monte Carlo Bootstrapping analysis procedure. Since electric field changes are indicative of changes in the underlying generator configuration (e.g., Fender, 1987; Lehmann, 1987), this test provides a statistical means of determining if and when the brain network activated by Ch, Ps and VM in each location differ.

#### 7.3.7.5 Topographic pattern analysis

NumTF (ms)	Number of time points when a microstate topographic map is observed
Onset (ms)	Point of time when a microstate topographic map starts
Offset (ms)	Point of time when a microstate topographic map ends
TFMax (ms)	Point of time when the GFP of a microstate topographic map reaches its maximum
MaxGFP ( $\mu\text{V}$ )	Maximal GFP value of a microstate topographic map
MeanGFP ( $\mu\text{V}$ )	Mean GFP value of a microstate topographic map

Table 7.1 Temporal and strength measures obtained for template maps in the spatial clustering step of topographic pattern analysis.

After the TANOVAs identified several phases of topographic modulations<sup>6</sup>, topographic pattern analysis was performed to determine whether topographic differences observed above were explainable by a single or multiple configuration changes or alternatively by a latency shift across conditions. Electrical configuration at the scalp does not vary randomly as a function of time, but rather exhibits stability for tens to hundreds of milliseconds with brief intervening intervals of topographic instabilities (Lehamann, 1987; Michel et al., 1999). Firstly, for each period of topographic modulations identified in the proceeding steps, a spatial clustering algorithm was applied to the group-averaged data under each of the 12 experimental conditions to obtain one or more template maps which best represented the EEG scalp distributions during that particular time window. Temporal and strength properties of each template map, as listed in Table 7.1, were also measured as part of this clustering algorithm. Next, by fitting the template maps obtained from the group-average data back onto individual participants, it can be determined if a given period of the ERP for a given experiment condition from a given participant is more often described by one

<sup>6</sup> A period of topographic modulation refers to a period during which ERP scalp distribution is significantly modulated by experiment conditions.

template map rather than another by comparing map occurrence frequency (measured as NumTF, see Table 7.1 for explanation). Once a most representative map was determined for a period of topographic modulations under each condition, other temporal and strength measures in Table 7.1 of that particular map were then subjected to a repeated measures ANOVA using the 12 experiment condition and template map as within-subject factors. Most of previous studies in the literature analyzed periods of topographic modulations which were no longer than 80 ms and thus aimed to identify one single map with the greatest occurrence frequency for that period. However, when a period of topographic modulations lasts a substantial amount of time and prior knowledge suggests that there exist distinct functional microstates during this time, it is unreasonable to have the template maps representing different functional microstates compete with each other and to determine whether one map appeared for greater amount of time than others during that particular period. For example, as shown in Figure 7.9 in the Results section, continuous topographic modulations were observed over the period of 140-265 ms in the previous step and this period spanned several ERPs, the ipsilateral P1, the contralateral N1, the ipsilateral N1 and the P2. In this case, a non-competitive fitting was performed on individual participants' data. Specifically, template topographic maps obtained in the earlier spatial clustering were considered as, in their temporal sequence, best describing the topographic changes over time during 140-265 ms (see Section 1.4.2 for details) and a Map\*Condition ANOVA was conducted for each map measure in Table 7.1, respectively.

#### 7.3.7.6 Source estimation analysis

As the final step of ERP analyses, standardized low resolution brain electromagnetic tomography (sLORETA, Pasqual-Marqui, 2002) was used to estimate the brain sources that significantly differentiated between stimulus conditions during

those POIs where significantly different scalp potential maps were identified. Specifically, for each POI exhibiting topographic differences between stimulus types, an averaged sLORETA image was defined as the average of all instantaneous sLORETA images within that time segment. Localization inference was based on paired comparisons of averaged sLORETA images for different stimulus conditions. 5000 randomization statistical non-parametric mapping were performed.

## 7.4 Results

### 7.4.1 Behavioral results

As mentioned when the Reicher-Wheeler task was first introduced back in Section 1.4, it is not one of the online tasks which encourage quick responses. Instead, the Reicher-Wheeler task emphasizes as accurate responses as possible. Therefore, participants would normally be instructed to take their time to make a decision and only response accuracy data is analyzed for statistical differences, as in Experiments 2-4 in the present thesis. However, Experiment 5 was different in that multiple head-mounted devices were used in this experiment and there were more stringent requirements on participants' movements for data-recording purpose. Not only did the eye tracker restrict head movements, but more importantly, even slight muscle tightening in the jaws or in the shoulder would create artifacts in EEG data. To help with the eye strain and general fatigue caused by these factors, it was advisable to control the overall running time of the experiment. Therefore, a response time constraint of 1500 ms was imposed on each trial for participants to make a choice, which made response time data more informative in judging how well participants could perform under different experimental conditions compared to in a Reicher-Wheeler task without a response time constraint. Besides, it would be interesting to compare the patterns of behavioural response times and ERP

response times and their implications.

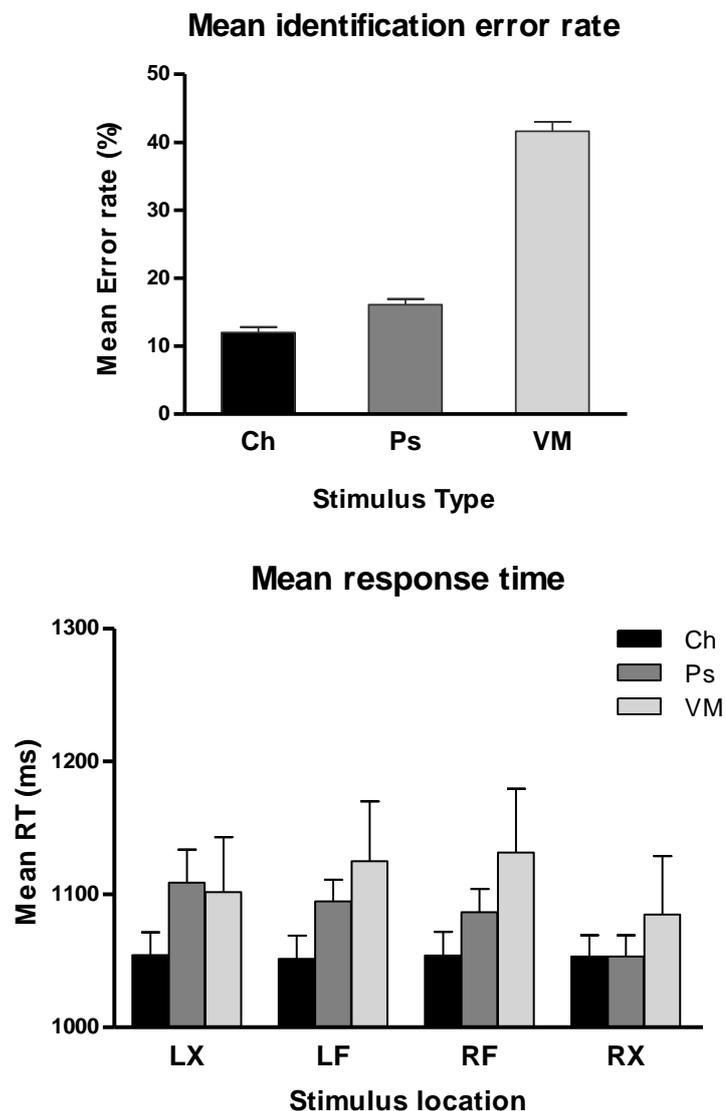


Figure 7.4. Behavioural results of Experiment 5. 'Ch', 'Ps' and 'VM' are abbreviations for characters, pseudocharacters, and visual matches of characters, respectively. 'LX', 'LF', 'RF' and 'RX' stand for the four screen locations for stimuli presentation from left to right, i.e., the extrafoveal position in the left visual field (2 deg), foveal position in the left visual field (0.15 deg), foveal position in the right visual field (0.15 deg), and extrafoveal position in the right visual field (2 deg). Bars depict standard errors.

For the above reasons, a repeated measures three-way ANOVA (Eccentricity\*VisField\*Stimulus) was performed on response error rate and reaction time respectively. The means of either measure for each of the experimental conditions

were plotted in Figure 7.4. A significant main effect of stimulus was found for error rate ( $F_{(2,15)} = 412.01, p < .01, \eta_p^2 = .97$ ). To further determine which stimulus types were different from each other, post-hoc comparisons were conducted and results revealed that participants were more accurate in the character condition than in the pseudocharacter condition while making the most errors in the VM condition (12%, 16%, and 42%, respectively,  $ps < .05$ ). Visual field or eccentricity did not affect identification accuracy for any of the stimulus types. Planned comparison was conducted between the size of character superiority over pseudocharacters in either visual field and found no visual field difference either.

For RT, the full  $2 \times 2 \times 3$  ANOVA revealed main effects of VisField ( $F_{(1,15)} = 14.62, p < .05, \eta_p^2 = .59$ ) and Eccentricity ( $F_{(1,15)} = 13.33, p < .01, \eta_p^2 = .57$ ), two-way interactions of Eccentricity  $\times$  VisField ( $F_{(1,15)} = 12.29, p < .01, \eta_p^2 = .55$ ), VisField  $\times$  Stimulus ( $F_{(2,15)} = 4.84, p < .05, \eta_p^2 = .33$ ), and Eccentricity  $\times$  Stimulus ( $F_{(2,15)} = 3.75, p < .05, \eta_p^2 = .28$ ) and finally a three-way interaction of Eccentricity  $\times$  VisField  $\times$  Stimulus ( $F_{(2,15)} = 3.95, p < .05, \eta_p^2 = .28$ ). Post-hoc comparisons for the Eccentricity  $\times$  VisField interaction showed that RTs for pseudocharacter stimuli outside of the fovea were longer when they were presented in the LVF than when presented in the RVF (1109 ms vs 1053 ms,  $p < .01$ ). Post-hoc comparisons for the VisField  $\times$  Stimulus interaction showed increased RTs to pseudocharacters when they were presented in the LVF relative to when presented in the RVF (1070 ms vs 1102 ms,  $p < .01$ ). Post-hoc comparisons for the three-way interaction revealed that RTs for pseudocharacter and VM stimuli in the RVF were shorter when they were presented extrafoveally compared to when presented foveally (1053 vs 1087 ms and 1085 vs 1132 ms, respectively,  $ps < .01$ ). However, due to the massive variances under the VM conditions (as reflected in the larger error bars on VM

mean RT across stimulus locations in Figure 7.4), the full ANOVA was unable to detect any significant difference between RTs to VM stimuli versus RTs to characters or pseudocharacters, though the latter two were different across all locations except in the RX. Therefore, a  $2 \times 2 \times 2$  version of the same ANOVA (Eccentricity\*VisField\*Stimulus) was conducted with the VM conditions removed. The same main effect of VisField and two-way interactions revealed in the full ANOVA were found again. More importantly, a main effect of stimulus showed that RTs for characters were significantly shorter compared to pseudocharacters (1053 vs. 1086 ms,  $F_{(1,15)} = 30.40$ ,  $p < .01$ ,  $\eta_p^2 = .75$ ). In addition, an Eccentricity  $\times$  VisField  $\times$  Stimulus interaction effect was also significant ( $F_{(1,7)} = 14.42$ ,  $p < .01$ ,  $\eta_p^2 = .59$ ) and post-hoc comparisons revealed shorter RT for characters relative to pseudocharacters except in the RX presentation and shorter RT for pseudocharacters in the RVF than in the LVF only in extrafoveal presentation (1053 ms vs. 1109 ms,  $p < .01$ ) but not in foveal presentation.

To sum up the major findings of behavioural results, response accuracy and time showed no effect of visual field or eccentricity on character identification. Like in central display, the character superiority over pseudocharacters and VMs in terms of response accuracy was also obtained in lateralized display irrespective of visual field and eccentricity. In terms of behavioural response time, faster responses to characters compared to pseudocharacters were observed except in the RX position. It is worth noting that this was mainly due to improved performance for pseudocharacters in the RX position rather than to declined character performance in the same position (see Figure 7.4 above). More importantly, although participants' responses to pseudocharacters were affected by their presentation locations, the eventual response accuracy for pseudocharacters was the same across all four screen locations. Besides,

the absence of visual field effect on character recognition (response accuracy or time), even when presented for merely 17 ms, seems to suggest that the two hemispheres play a balanced role in Chinese character recognition. However, it still requires ERP evidence to determine whether the two hemispheres are equally involved throughout all stages of character processing or there do exist hemispheric asymmetries the pattern of which may vary along the time course.

#### 7.4.2 ERP results

Unlike the statistic analysis of the behavioral data which was achieved by two repeated measures ANOVAs (on error rate and RT, respectively), analyses of the ERP data were more complicated in that separate ANOVAs were applied to a wider range of dependent variables (such as electrode and hemisphere) within various time windows (such as the P1 and the N1), which accordingly yielded a larger number of effects than in the behavioral results. For the sake of information relevance and readability, when post-hoc comparisons were required to further explore an effect, only means of the conditions that significantly differed in post-hoc comparisons are reported in the text, followed by relevant post-hoc p values; all other statistics including F and  $\eta^2$  values are summarized in Table 7.2 instead of immediately following their corresponding effects in the text.

This section will be structured according to the steps of analyses laid out in Section 7.3.7, where the rationale for each of those steps was also explained. Specifically,

ERP	Measure	Sig effects and stats	ERP	Measure	Sig effects and stats
P1	Latency	VisField*Hemisphere O1_O2, F(1,7)= 58.68, $p < .01$ , $\eta_p^2 = .91$ PO7_PO8, F(1,7) = 102.12, $p < .001$ , $\eta_p^2 = .95$ P7_P8, F(1,7) = 10.41, $p < .05$ , $\eta_p^2 = .63$	P2	Latency	None
		Eccentricity*VisField O1_O2, F(1,7) = 8.43, $p < .05$ , $\eta_p^2 = .58$ PO7_PO8, F(1,7) = 9.54, $p < .05$ , $\eta_p^2 = .61$ P7_P8, F(1,7) = 10.41, $p < .05$ , $\eta_p^2 = .63$		Amplitude	Eccentricity FC1_FC2, F(1,7) = 10.41, $p < .05$ , $\eta_p^2 = .57$ C3_C4, F(1,7) = 19.38, $p < .01$ , $\eta_p^2 = .71$ CP1_CP2, F(1,7) = 17.46, $p < .01$ , $\eta_p^2 = .69$ Stimulus FC1_FC1, F(2,7) = 36.39, $p < .001$ , $\eta_p^2 = .82$ C3_C4, F(2,7) = 25.03, $p < .01$ , $\eta_p^2 = .76$ CP1_CP2, F(2,7) = 16.37, $p < .01$ , $\eta_p^2 = .60$
	Amplitude	Stimulus PO7_PO8, F(2,7) = 5.36, $p < .05$ , $\eta_p^2 = .47$ P7_P8, F(2,7) = 11.33, $p < .05$ , $\eta_p^2 = .65$		Amplitude (VM excluded)	Stimulus FC1_FC2, F(1,7) = 8.54, $p < .05$ , $\eta_p^2 = .52$ C3_C4, F(1,7) = 19.38, $p < .01$ , $\eta_p^2 = .71$ CP1_CP2, F(1,7) = 17.46, $p < .01$ , $\eta_p^2 = .69$ VisField*Hemisphere*Stimulus FC1_FC2, F(2,7) = 3.95, $p < .05$ , $\eta_p^2 = .27$ CP1_CP2, F(2,7) = 30.92, $p < .01$ , $\eta_p^2 = .79$
		Eccentricity P7_P8, F(1,7) = 8.89, $p < .05$ , $\eta_p^2 = .60$ VisField*Hemisphere O1_O2, F(1,7) = 6.20, $p < .05$ , $\eta_p^2 = .51$ PO7_PO8, F(1,7) = 11.47, $p < .05$ , $\eta_p^2 = .66$ P7_P8, F(1,7) = 17.49, $p < .01$ , $\eta_p^2 = .75$ Eccentricity*VisField*Hemisphere P7_P8, F(1,7) = 7.34, $p < .05$ , $\eta_p^2 = .55$ Eccentricity*VisField*Stimulus P7_P8, F(2,7) = 4.87, $p < .05$ , $\eta_p^2 = .45$		Latency	Eccentricity PO3_PO4, F(1,7) = 16.28, $p < .01$ , $\eta_p^2 = .73$ P3_P4, F(1,7) = 18.99, $p < .01$ , $\eta_p^2 = .76$ P7_P8, F(1,7) = 24.52, $p < .01$ , $\eta_p^2 = .80$ VisField*Hemisphere PO3_PO4, F(1,7) = 29.88, $p < .01$ , $\eta_p^2 = .83$
N1	Latency	VisField*Hemisphere O1_O2, F(1,7) = 19.96, $p < .01$ , $\eta_p^2 = .77$ PO7_PO8, F(1,7) = 28.46, $p < .01$ , $\eta_p^2 = .83$ P7_P8, F(1,7) = 38.14, $p < .01$ , $\eta_p^2 = .86$	P3	Amplitude	Eccentricity PO3_PO4, F(1,7) = 21.51, $p < .01$ , $\eta_p^2 = .78$ P3_P4, F(1,7) = 14.29, $p < .01$ , $\eta_p^2 = .70$ P7_P8, F(1,7) = 9.77, $p < .05$ , $\eta_p^2 = .62$ Stimulus P3_P4, F(2,7) = 5.32, $p < .05$ , $\eta_p^2 = .47$ VisField*Hemisphere PO3_PO4, F(1,7) = 4.99, $p = .05$ , $\eta_p^2 = .45$ Stimulus*Hemisphere F(1,7) = 4.99, $p = .05$ , $\eta_p^2 = .45$
	Amplitude	Stimulus O1_O2, F(2,7) = 3.97, $p < .05$ , $\eta_p^2 = .40$ Hemisphere P7_P8, F(1,7) = 10.86, $p < .05$ , $\eta_p^2 = .64$ VisField*Hemisphere P7_P8, F(1,7) = 10.92, $p < .05$ , $\eta_p^2 = .65$ Eccentricity*VisField*Hemisphere*Stimulus O1_O2, F(2,7) = 5.37, $p < .05$ , $\eta_p^2 = .47$			

Table 7.2 Summary table of the ERP peak analysis results. Post-hoc comparison means, F, p, and  $\eta_p^2$  values were described in the text where relevant.

the ERP results starts with the time-and-electrode-specific peak analysis and the more comprehensive point-wise waveform comparisons, followed by TANOVAs which test whether the ERP waveform differences identified earlier were due to topographic modulations and the topographic pattern analysis which examined how exactly the global configurational map varied under different experimental conditions, and finally by the sLORETA which statistically determine whether the topographic pattern differences identified in the proceeding steps could be attributed to changes in certain underlying generators.

#### 7.4.2.1 Results of ERP peak analysis

As noted in the Methodology section (Section 7.3.7), four major peaks (P1, N1, P2 and P3) were identified in the ERP data and hence only these four peaks were submitted to peak analysis. As pointed out in Section 7.1.2 where the C1 was first

introduced, it is a peak that has been missing in almost all language-related studies due to its weak strength and low incidence compared to other major peaks. The C1 did not show identifiable peaks in the present study, either, though this initial stage of brain processing was examined in following steps of ERP analyses. In a similar vein, the N400 was not included in peak analysis due to the 500-ms cutoff in the present study though the primitive state of this component was analyzed in other ERP analyses.

### **P1**

The repeated-measures ANOVA on P1 latency found two interaction effects common to all the three pairs of electrodes under examination, i.e., Hemisphere\*VisField and Eccentricity\*VisField. Post-hoc comparisons for the VisField\*Hemisphere interaction further revealed that, regardless of foveal or extrafoveal presentation, stimuli in the LVF had a shorter latency in the contralateral RH than in the ipsilateral LH and vice versa (O1\_O2: 111 ms in the RH vs 142 ms in the LH for the LVF presentations, 100 ms in the LH vs 142 ms in the RH for the RVF presentations; PO7\_PO8: 107 ms in the RH vs 142 ms in the LH for the LVF presentations, 99 ms in the LH vs 142 ms in the RH for the RVF presentations; P7\_P8: 106 ms in the RH vs 141 ms in the LH for the LVF presentations, 97 ms in the LH vs 143 ms in the RH for the RVF presentations;  $ps < .05$ ). Post-hoc comparisons for the Eccentricity\*VisField interaction revealed that, when presented extrafoveally, stimuli in the RVF had a shorter overall latency than those in the LVF (120 vs 133 ms,  $ps < .05$ ); also, in the LVF, foveally presented stimuli had a shorter overall latency than extrafoveally presentation stimuli (121 vs 133 ms,  $ps < .05$ ). No other significant effects were found.

The repeated-measures ANOVA on the P1 amplitude revealed different effects for different electrode pairs. Firstly, a two-way interaction between visual field and

hemisphere was common to all the electrode pairs with greater responses in the LH than in the RH for LVF stimuli (O1\_O2: 3.5 vs 2.1  $\eta$ V; PO7\_PO8: 4.3 vs 2.4  $\eta$ V; P7\_P8: 3.6 vs 1.6  $\eta$ V;  $p$ s < .05). Secondly, a main effect of stimulus was found for both PO7\_PO8 and P7\_P8 with higher amplitudes for pseudocharacters compared to characters and VMs (PO7\_PO8: 4.0 vs 3.6 vs 3.2  $\eta$ V; P7\_P8: 3.1 vs 2.8 vs 2.3  $\eta$ V;  $p$ s < .05). In addition, a main effect of eccentricity (3.0  $\eta$ V for extra vs 2.4  $\eta$ V for fovea) and two three-way interactions (Eccentricity\*VisField\*Hemisphere and Eccentricity\*VisField\*Stimulus) were significant for P7\_P8 comparisons. Post-hoc comparisons for the Eccentricity\*VisField\*Hemisphere interaction revealed that the difference between extrafovea and fovea conditions, as described in the main effect, was evident except in the RH for LVF presentations (LF vs LX in the LH: 3.1 vs 4.0  $\eta$ V; RF vs RX in the LH: 2.0 vs 3.3  $\eta$ V; RF vs RX in the RH: 2.5 vs 3.8  $\eta$ V;  $p$ s < .05). Post-hoc comparisons for the Eccentricity\*VisField\*Stimulus interaction found that P1 amplitude for the VM stimuli when presented in the LVF showed an eccentricity difference in the opposite direction of the main effect of eccentricity, namely, brain responses to LX\_VM stimuli were weaker than those to LF\_VM ones (1.5 vs 2.5  $\eta$ V,  $p$  < .05). Similarly, when VMs were presented extrafoveally, P1 amplitude under the LX\_VM condition was smaller than under the RX\_VM condition (1.5 vs 3.2  $\eta$ V,  $p$  < .05). Moreover, reduced amplitude for characters compared to pseudocharacters was found only in the RF location (2.1 vs 2.7  $\eta$ V,  $p$  < .05). Note that there was also a tendency of VM peaks smaller than pseudocharacter peaks though the difference was not significant due to massive SD of VMs.

## N1

The repeated-measures ANOVA on N1 latency only found the VisField\*Hemisphere interaction which was common to all the three pairs of electrodes.

Specifically, as in the P1 component, the N1 latency for the LVF stimuli was shorter in the contralateral RH than in the ipsilateral LH and vice versa (O1\_O2: 172 ms in the RH vs 194 ms in the LH for LVF presentations, 176 ms in the LH vs 194 ms in the RH for RVF presentations; PO7\_PO8: 165 ms in the RH vs 195 ms in the LH for LVF presentations, 175 ms in the LH vs 195 ms in the RH for RVF presentations; P7\_P8: 165 ms in the RH vs 195 ms in the LH for LVF presentations, 171 ms in the LH vs 196 ms in the RH for RVF presentations;  $p < .01$ ).

The repeated-measures ANOVA on N1 amplitude had the following results. For O1\_O2, there were a main effect of stimulus and a four-way interaction. Post-hoc comparisons for the stimulus effect showed greater brain activities for characters than for VMs ( $-3.2$  vs  $-2.5$   $\eta$ V,  $p < .05$ ). More importantly, post-hoc tests for the four-way interaction further revealed that it was in the LH that LF characters produced greater amplitude than the LF VMs ( $-4.4$  vs  $-2.5$   $\eta$ V,  $p < .05$ ), though there was also a tendency of LF characters having greater amplitude than LF pseudocharacters in the LH ( $p = 0.08$ ). In addition, the LH was shown to be more responsive to LF characters than to LX characters ( $-4.4$  vs  $-2.4$   $\eta$ V,  $p < .05$ ), though the LH also exhibited such a tendency between RF characters and RX characters ( $p = 0.07$ ). Also in the LH, there was a RF presentation advantage over LF presentation for pseudocharacters ( $-4.4$  vs  $-2.2$   $\eta$ V) and VMs ( $-4.0$  vs  $-2.5$   $\eta$ V) ( $p < .05$ ). For PO7\_PO8, only the main effect of stimulus was found with a character advantage over VM ( $-4.0$  vs  $-3.2$   $\eta$ V,  $p < .01$ ). For P7\_P8, there was a main effect of Hemisphere with the LH showing greater activation than the RH ( $-4.8$  vs  $-2.9$   $\eta$ V,  $p < .05$ ) and a VisField\*Hemisphere interaction. Post-hoc comparisons for the interaction revealed that the LH had higher amplitude than the RH only for RVF presentations ( $-6.0$  vs  $-1.6$   $\eta$ V,  $p < .01$ ); besides, both hemispheres showed higher amplitude for stimuli from their contralateral visual field than for stimuli

from their ipsilateral visual field ( $p < .05$ ).

## **P2**

The repeated-measures ANOVA on the P2 latency found no significant effect. In terms of amplitude, only two main effects were found and they were common to FC1\_FC2, C3\_C4 and CP1\_CP2. Firstly, all the electrode pairs showed the main effect of eccentricity with greater amplitude for extrafoveal presentations than for foveal presentations (FC1\_FC2: 7.2 vs 5.9  $\eta$ V; C3\_C4: 6.3 vs 4.9  $\eta$ V; CP1\_CP2: 6.3 vs 4.5  $\eta$ V;  $ps < .01$ ). Secondly, they all showed the main effect of stimulus with characters and pseudocharacters eliciting larger P2 peaks than VMs (FC1\_FC2: 7.3 vs 7.7 vs 4.8  $\eta$ V; C3\_C4: 6.1 vs 6.5 vs 4.2  $\eta$ V; CP1\_CP2: 5.8 vs 6.3 vs 4.1  $\eta$ V;  $ps < .01$ ). In addition, when VM excluded from analysis, difference between characters and pseudocharacters further emerged with greater P2 peaks elicited by pseudocharacters relative to characters for all the three pairs of electrodes ( $ps < .05$ ). Moreover, a Stimulus\*VisField\*Hemisphere interaction was also found on the FC1\_FC2 and CP1\_CP2 sites. Specifically, they all showed larger P2 peaks in response to pseudocharacters compared to characters in the RH when stimuli were presented in the RVF (FC1\_FC2: 8.2 vs 7.4  $\eta$ V; CP1\_CP2: 6.4 vs 5.8  $\eta$ V;  $ps < .05$ ). For CP1\_CP2, it was also found that characters elicited higher P2 amplitude in the RH compared to the LH when they were presented in the LVF (6.1 vs 5.5  $\eta$ V,  $p < .05$ ).

## **P3**

The repeated-measures ANOVA on P3 latency found two significant effects common to all the three pairs of electrodes under examination, a main effect of eccentricity with foveal presentations showing later P3 peaks than extrafoveal presentations (PO3\_PO4, 335 vs 315 ms; P3\_P4, 334 vs 315 ms; P7\_P8, 334 vs 313 ms,  $ps < .01$ ) and a VisField\*Hemisphere interaction. Post-hoc tests revealed that the P3

peak latency for the LVF stimuli was shorter in the contralateral RH than in the ipsilateral LH and vice versa (PO3\_PO4, 322 ms in the RH vs 329 ms in the LH for LVF presentations, 321 ms in the LH vs 328 ms in the RH for RVF presentations; P3\_P4, 322 ms in the RH vs 328 ms in the LH for LVF presentations, 320 ms in the LH vs 327 ms in the RH for RVF presentations; P7\_P8, 321 ms in the RH vs 328 ms in the LH for LVF presentations, 320 ms in the LH vs 326 ms in the RH for RVF presentations,  $p < .05$ ).

The repeated-measures ANOVA on the P3 amplitude found the following results. There was a main effect of eccentricity common to all the three electrode pairs under examination with greater brain activity strength for extrafoveal presentations than for foveal ones (PO3\_PO4, 4.5 vs 3.0  $\eta V$ ; P3\_P4, 4.3 vs 2.7  $\eta V$ ; P7\_P8, 4.0 vs 3.1  $\eta V$ ,  $p < .01$ ). In addition, a main effect of stimulus was significant on the P3\_P4 sites with comparatively lower P3 amplitude for characters than for pseudocharacters (2.9 vs 3.8  $\eta V$ ,  $p < .05$ ) and approached significance on P7\_P8 ( $p = .07$ ). Furthermore, two interaction effects (VisField\*Hemisphere and Stimulus\*Hemisphere) were obtained on the PO3\_PO4 sites. Post-hoc comparisons for the former interaction showed larger P3 peaks in the RH relative to the LH when stimuli were presented in the LVF (4.5 vs 3.2  $\eta V$ ,  $p < .05$ ); post-hoc comparisons for the latter interaction showed larger P3 peaks for pseudocharacters versus characters in the RH (4.5 vs 3.5  $\eta V$ ,  $p < .05$ ) and for VM in the RH versus in the LH (4.2 vs 3.2  $\eta V$ ,  $p < .05$ ).

### **Summary of ERP peak analysis results**

The ERP peak analysis examined four components, the P1, the N1, the P200 and the P300. The N400 introduced at the beginning of the chapter was not included as the EEG segmentation ended at 500 ms.

One of the major findings of the ERP peak analysis is that the visual field of

presentation had a significant impact on the P1 peak latency in either hemisphere with the P1 latency being delayed in the hemisphere ipsilateral to the stimulated visual field relative to the contralateral hemisphere. More importantly, this latency delay occurred regardless of the eccentricity of presentation. This finding supports the 'unilateral projection' view of foveal processing that stimuli presented in either visual field within the fovea, like in the extrafovea, initially project to the contralateral hemisphere before transferring to the ipsilateral hemisphere. The initial-receiving hemisphere (depending on the stimulated visual field) also affected the P1 peak amplitude by showing a LH advantage over the RH in response to characters and character-like stimuli. Indeed, the influence of initial unilateral projection and its direction persisted until the P3 in the present study.

Although a split pattern of peak latency was observed for both extrafoveal and foveal presentations, they elicited significant latency and amplitude differences when compared against each other. More importantly, these differences often interacted with visual field, hemisphere and stimulus type (see above for details).

With regard to the impact of stimulus type, characters elicited different levels of ERP peak amplitude compared to pseudocharacters and/or VMs throughout P1 to P3. These stimulus effects in different ERPs, often modulated by the visual field and eccentricity of presentation and the hemisphere of recording, shed light on the various stages of brain processes involved in visual character recognition, from the more coarse-scale configurational information extraction to the more fine-scale feature analysis, from attempting lexical access to the internal evaluation of stimulus processing outcome, which will be discussed in detail in the following section.

#### 7.4.2.2 Results of ERP waveform t-tests

As explained in Section 7.3.7, traditional peak analysis applies to only a limited

number of electrode sites over a certain scalp area during a more constrained time window whereas the ERP waveform t-tests provide a macro view of waveform modulations over the entire scalp along the whole ERP epoch. The procedure of waveform t-tests is especially useful in comparing the patterns of ERP response when no peaks are available for peak analysis, for example, during the C1 time window when neural response is typically too weak for observable peaks. Specifically, point-wise paired t-tests were conducted to determine the timing of differences in ERP responses to different stimuli in each location. (LX\_Ch vs LX\_Ps; LX\_Ch vs LX\_VM; LX\_Ps vs LX\_VM and so on). A temporal criterion of 10 consecutive data points was applied. Specifically, for each electrode, the first time point where the t test exceeded the 0.05 alpha criterion for at least 10 consecutive data points (>10 ms at a 1000 Hz digitalization rate) was labeled as onset of an ERP modulation. Superimposed group-averaged ERP waveforms across electrodes in responses to each stimulus type in each presentation location and results of paired point-wise t-tests on waveforms are shown in Figure 7.5 and Figure 7.6, respectively.

The results show that the earliest ERP modulation appeared at approximately 60 ms post-stimulus for almost all comparisons. The offset of this early ERP difference occurred at approximately 100 ms. The next sustained period of ERP modulations occurred approximately between 140-265 ms. These effects were more prominent for comparisons between the VMs versus characters and pseudocharacters, affecting more electrodes for more time points, relative to when the latter two stimulus types were compared between themselves. Two subsequent periods of ERP response modulations followed, between 300-335 ms (more prominent for comparisons in the two extrafoveal locations) and 450-500 ms respectively. The onsets and offsets of the first three periods of waveform modulations roughly corresponded to the time windows during which

major ERP peaks observed in this experiment. Specifically, 60-100 ms corresponded to the early P1; 140-265 ms covered the late P1, the early and late N1, and the P2; 300-335 ms corresponded to the P3. As for the 450-500 ms, although the 0-500 ms epoch in this study ended before visible N400 peaks appeared and thus the preceding peak analyses did not include this late component, it is believed that this period corresponded to the N400 in this primitive stage. This assumption was confirmed in the topographic pattern analysis which will be discussed later.

In summary, the ERP point-wise waveform t-tests provided a more temporally comprehensive examination of the ERP activities than just comparing ERPs at their peak latencies. The results revealed four sustained periods in which the ERP waveforms were significantly modulated by stimulus type, which are 60-100 ms, 140-265 ms, 300-335 ms, and 450-500 ms.

## ERP waveforms for LX presentations

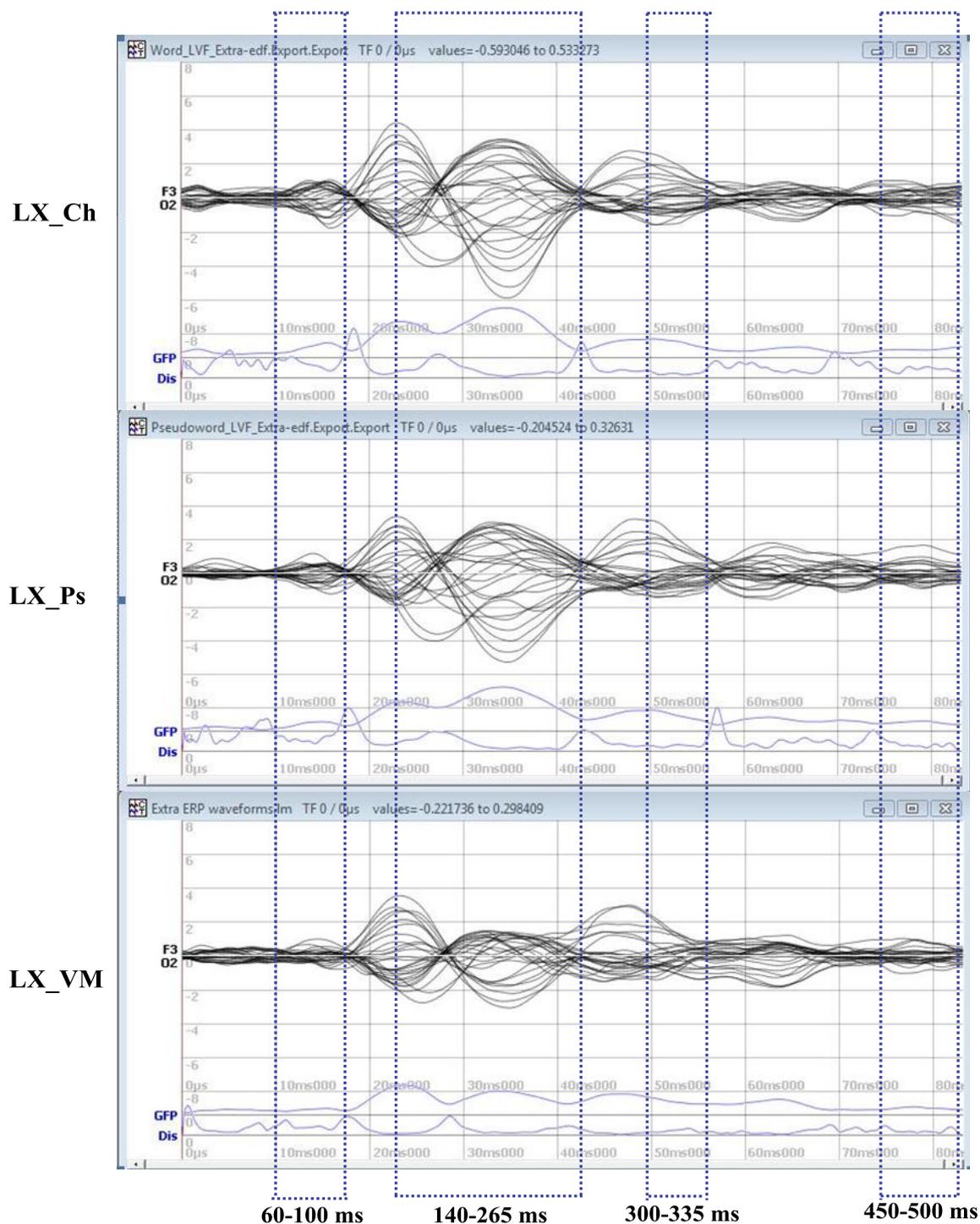


Figure 7.5-A. Superimposed group-averaged ERP waveforms in response to LX presentations on a scale of  $\pm 8 \mu\text{V}$ . From top to bottom are waveforms in response to LX\_Ch, LX\_Ps, and LX\_VM stimuli, respectively. The dot-outlined boxes indicate the POIs determined based on results of peak analysis, waveform  $t$ -tests and TANOVAs for further investigations of topographic pattern differences.

## ERP waveforms for LF presentations

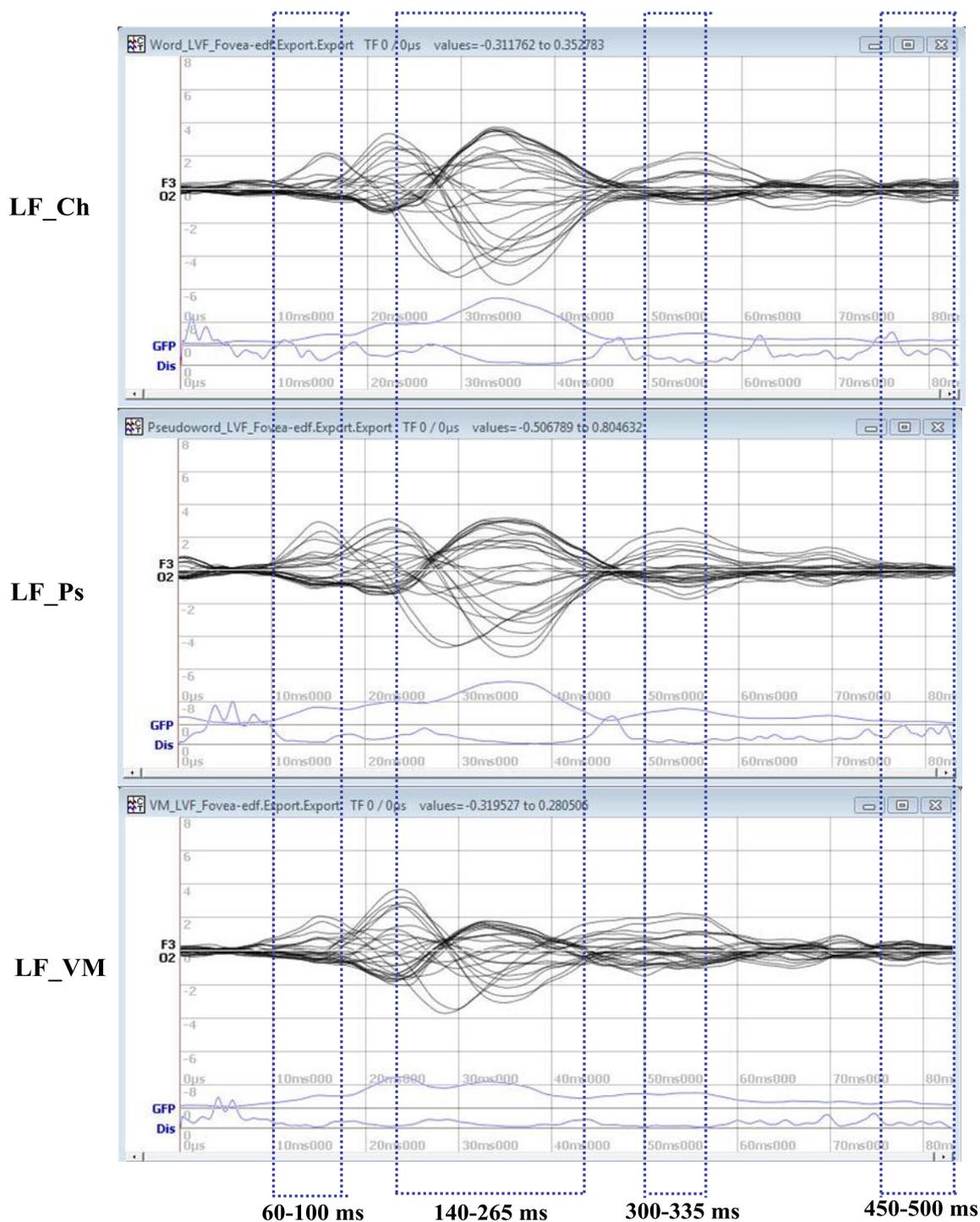


Figure 7.5-B. Superimposed group-averaged ERP waveforms in response to LF presentations on a scale of  $\pm 8 \mu\text{V}$ . From top to bottom are waveforms in response to LF\_Ch, LF\_Ps, and LF\_VM stimuli, respectively. The dot-outlined boxes indicate the POIs determined based on results of peak analysis, waveform  $t$ -tests and TANOVAs for further investigations of topographic pattern differences.

## ERP waveforms for RF presentations

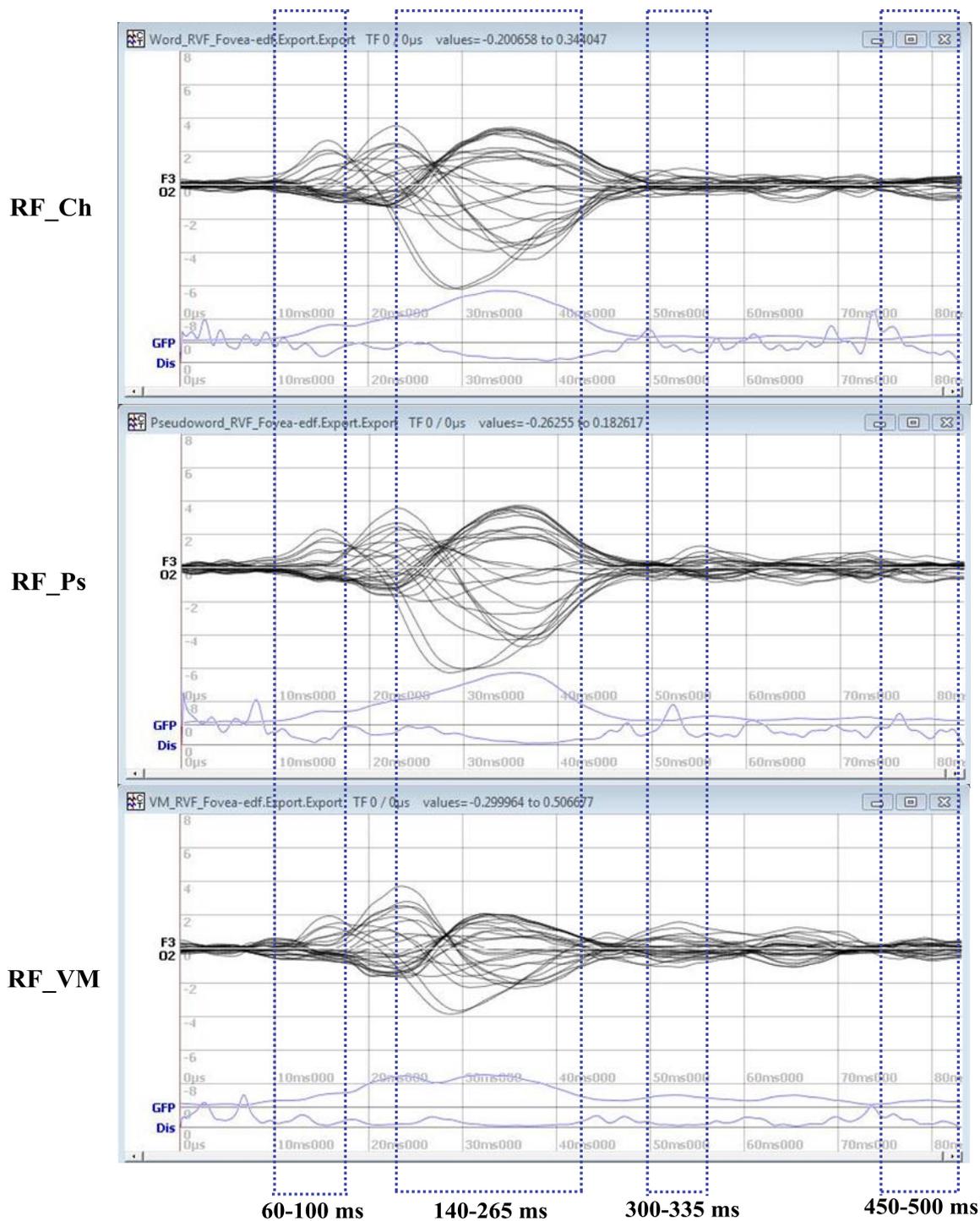


Figure 7.5-C. Superimposed group-averaged ERP waveforms in response to RF presentations on a scale of  $\pm 8 \mu\text{V}$ . From top to bottom are waveforms in response to RF\_Ch, RF\_Ps, and LF\_VM stimuli, respectively. The dot-outlined boxes indicate the POIs determined based on results of peak analysis, waveform  $t$ -tests and TANOVAs for further investigations of topographic pattern differences.

## ERP waveforms for RX presentations

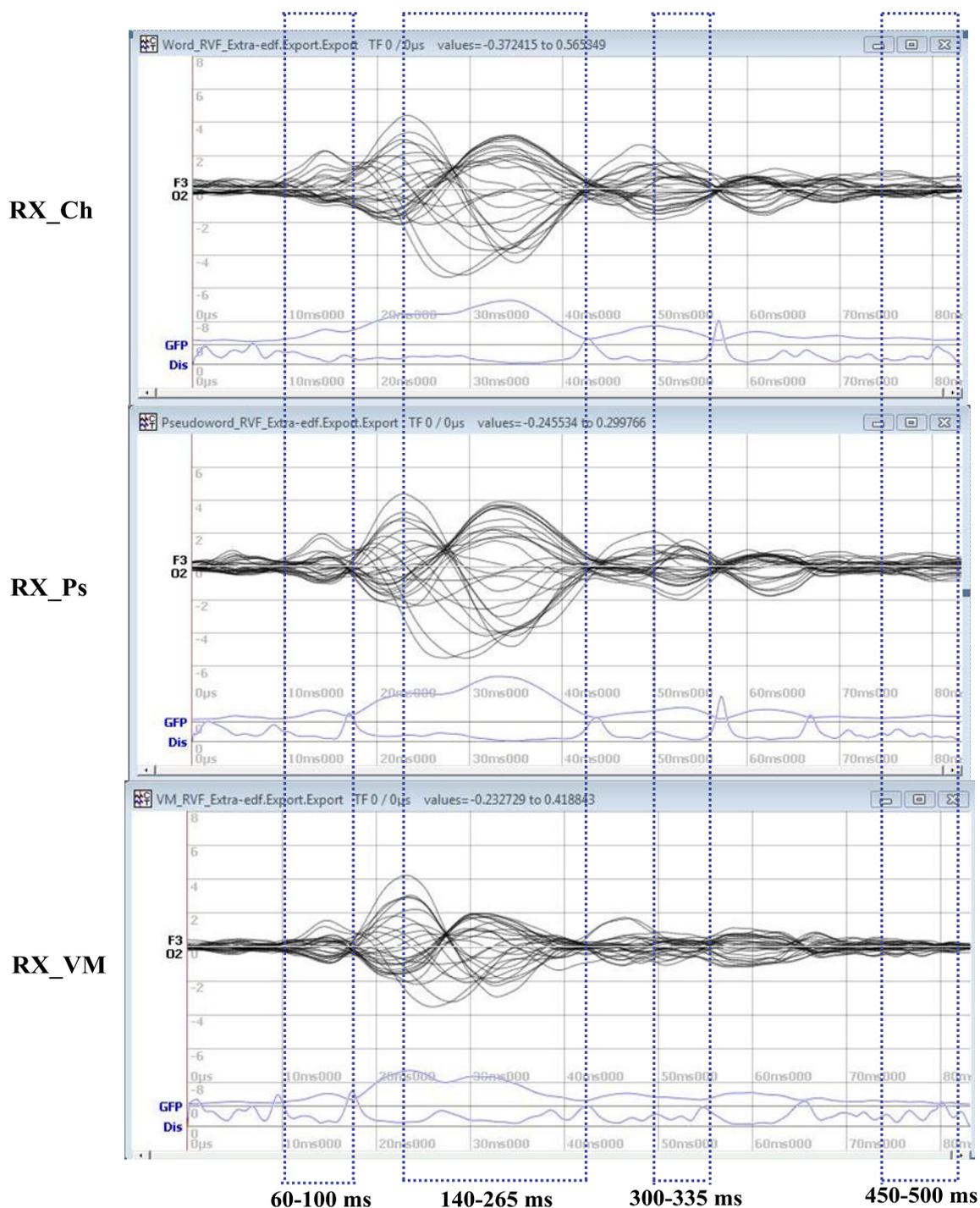


Figure 7.5-D. Superimposed group-averaged ERP waveforms in response to RX presentations on a scale of  $\pm 8 \mu\text{V}$ . From top to bottom are waveforms in response to RX\_Ch, RX\_Ps, and RX\_VM stimuli, respectively. The dot-outlined boxes indicate the POIs determined based on results of peak analysis, waveform  $t$ -tests and TANOVAs for further investigations of topographic pattern differences.

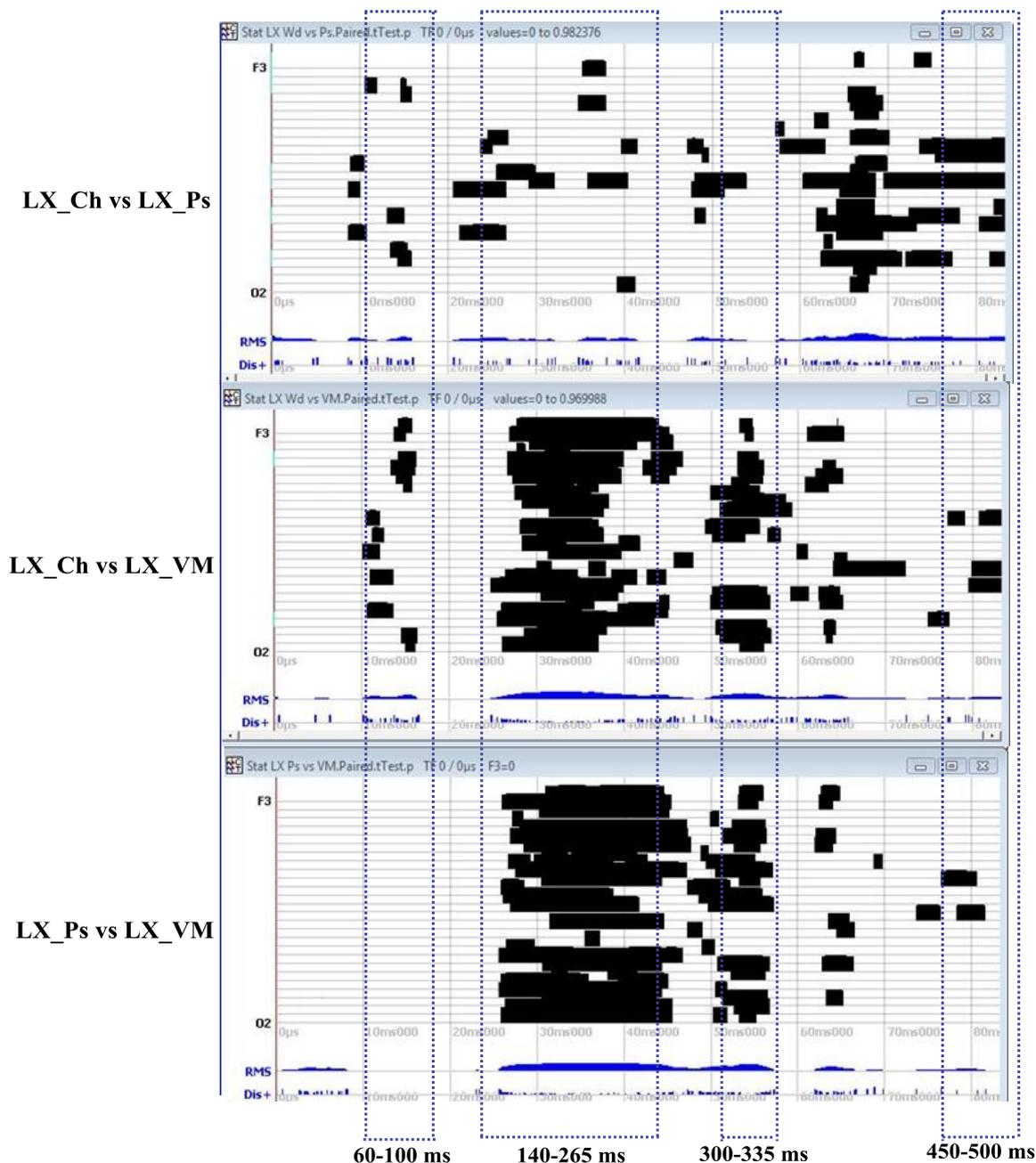
ERP waveform  $t$ -tests for LX presentations

Figure 7.6-A. Results of the ERP waveform point-wise  $t$ -tests between LX conditions. The top panel plots the results of paired  $t$ -test comparisons between the LX\_Ch and LX\_Ps stimuli, the middle panel the LX\_Ch and LX\_VM stimuli, and the bottom panel the LX\_Ps and LX\_VM stimuli. In each panel, electrode location is plotted along the y-axis with posterior sites near the origin, central sites further above and frontal sites furthest away. Significant ( $p < 0.05$ ) waveform differences are marked with black horizontal bars and only those appearing for at least 10 ms are shown. The dot-outlined boxes indicate the POIs determined based on results of peak analysis, waveform  $t$ -tests and TANOVAs for further investigations of topographic pattern differences.

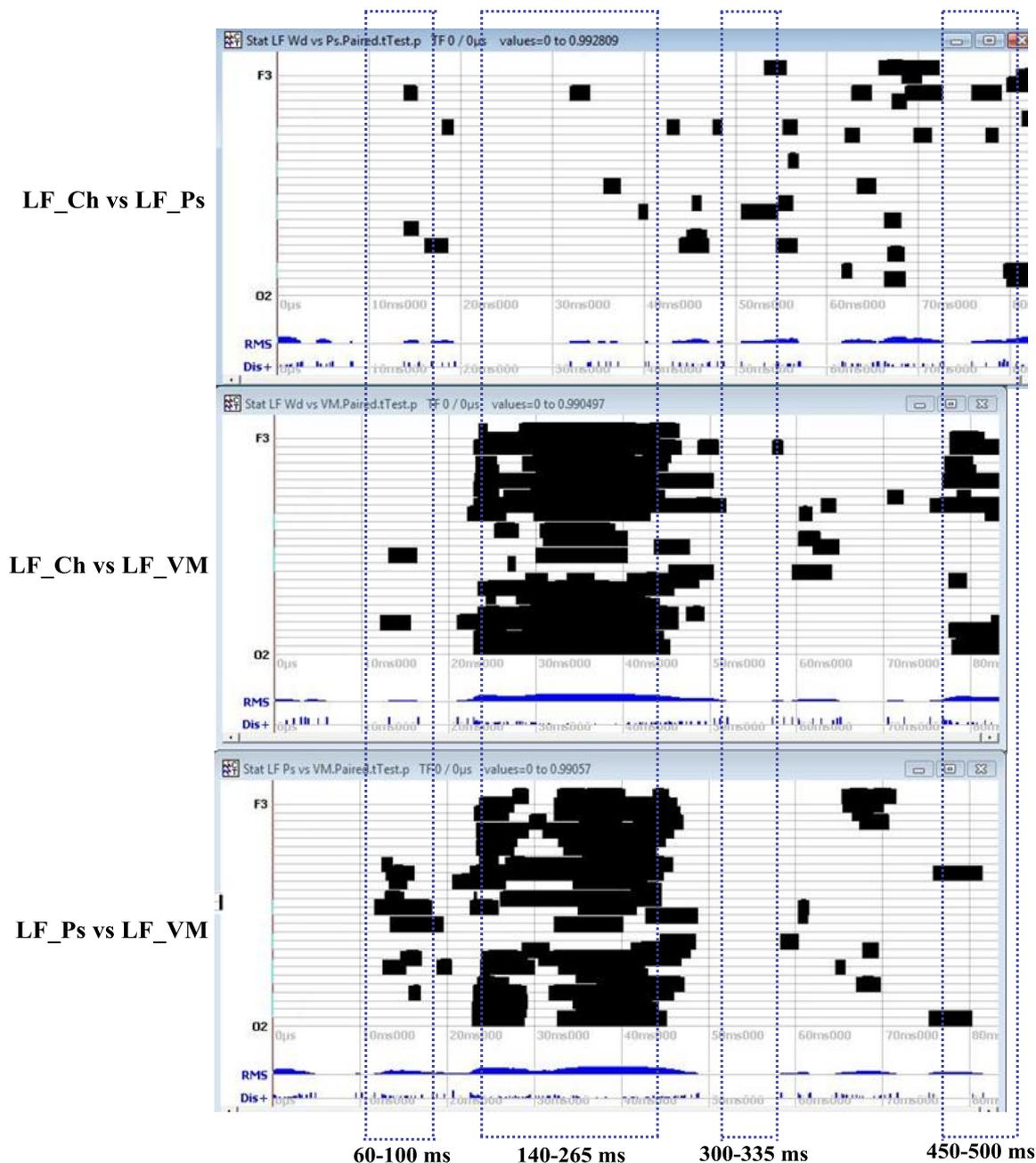
ERP waveform  $t$ -tests for LF presentations

Figure 7.6-B. Results of the ERP waveform point-wise  $t$ -tests between LF conditions. The top panel plots the results of paired  $t$ -test comparisons between the LF\_Ch and LF\_Ps stimuli, the middle panel the LF\_Ch and LF\_VM stimuli, and the bottom panel the LF\_Ps and LF\_VM stimuli. In each panel, electrode location is plotted along the y-axis with posterior sites near the origin, central sites further above and frontal sites furthest away. Significant ( $p < 0.05$ ) waveform differences are marked with black horizontal bars and only those appearing for at least 10 ms are shown. The dot-outlined boxes indicate the POIs determined based on results of peak analysis, waveform  $t$ -tests and TANOVA for further investigations of topographic pattern differences.

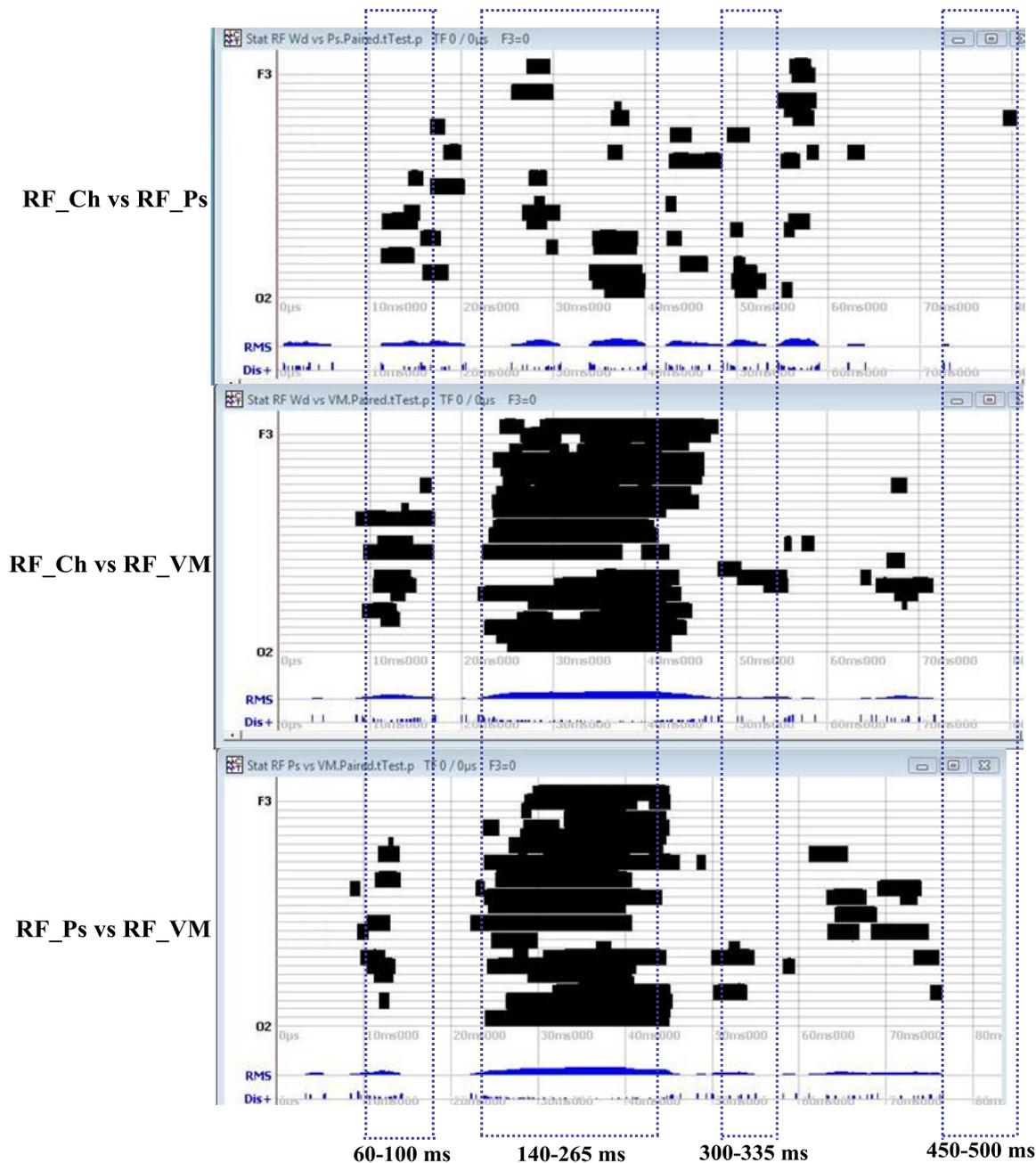
ERP waveform  $t$ -tests for RF presentations

Figure 7.6-C. Results of the ERP waveform point-wise  $t$ -tests between RF conditions. The top panel plots the results of paired  $t$ -test comparisons between the RF\_Ch and RF\_Ps stimuli, the middle panel the RF\_Ch and RF\_VM stimuli, and the bottom panel the RF\_Ps and RF\_VM stimuli. In each panel, electrode location is plotted along the y-axis with posterior sites near the origin, central sites further above and frontal sites furthest away. Significant ( $p < 0.05$ ) waveform differences are marked with black horizontal bars and only those appearing for at least 10 ms are shown. The dot-outlined boxes indicate the POIs determined based on results of peak analysis, waveform  $t$ -tests and TANOVA for further investigations of topographic pattern differences.

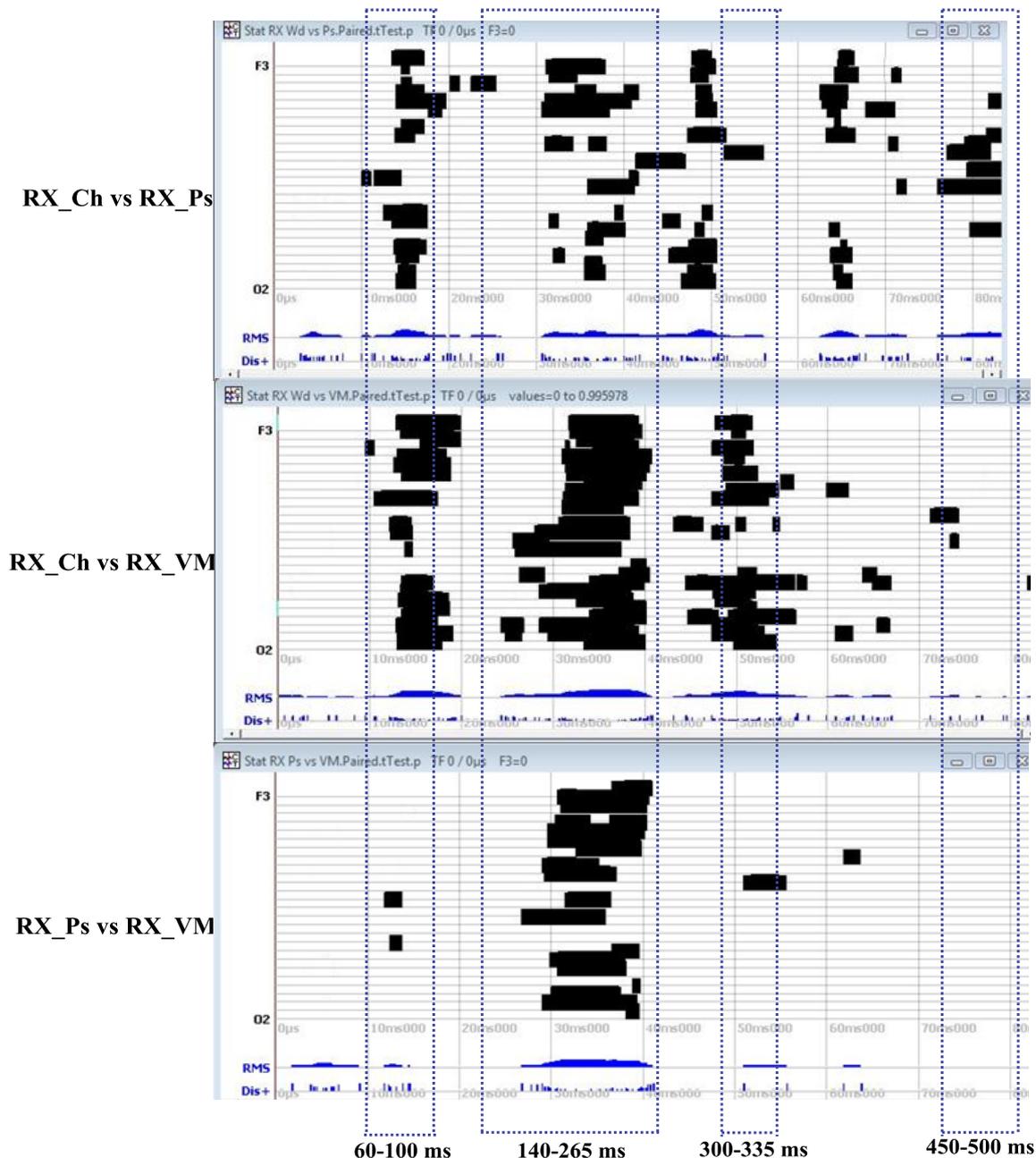
ERP waveform  $t$ -tests for RX presentations

Figure 7.6-D. Results of the ERP waveform point-wise  $t$ -tests between RX conditions. The top panel plots the results of paired  $t$ -test comparisons between the RX\_Ch and RX\_Ps stimuli, the middle panel the RX\_Ch and RX\_VM stimuli, and the bottom panel the RX\_Ps and RX\_VM stimuli. In each panel, electrode location is plotted along the y-axis with posterior sites near the origin, central sites further above and frontal sites furthest away. Significant ( $p < 0.05$ ) waveform differences are marked with black horizontal bars and only those appearing for at least 10 ms are shown. The dot-outlined boxes indicate the POIs determined based on results of peak analysis, waveform  $t$ -tests and TANOVAs for further investigations of topographic pattern differences.

## TANOVAs for LX presentations

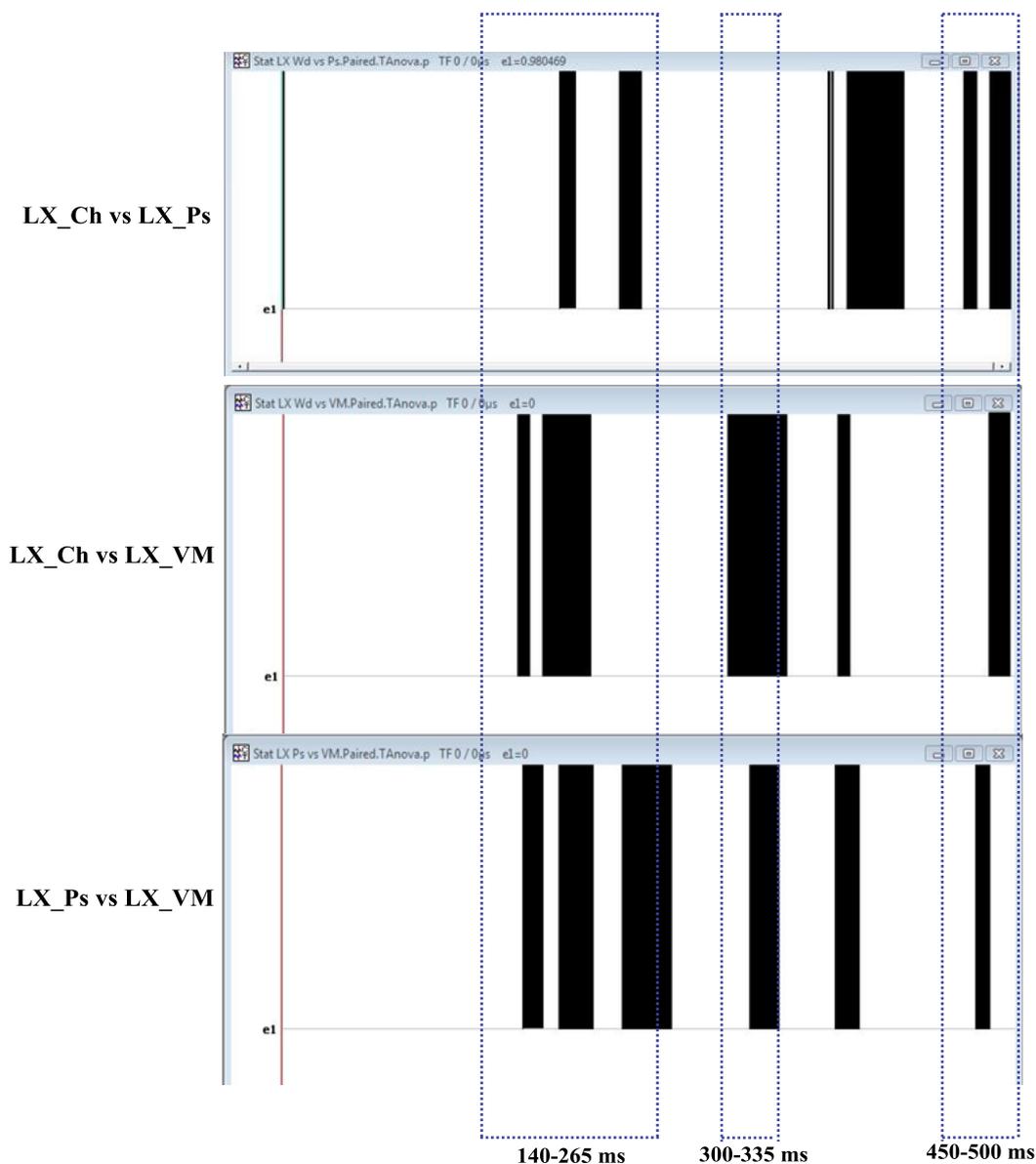


Figure 7.7-A. Results of point-wise TANOVAs between LX conditions. The top panel shows the results of TANOVA comparisons between the LX\_Ch and LX\_Ps stimuli, the middle panel the LX\_Ch and LX\_VM stimuli, and the bottom panel the LX\_Ps and LX\_VM stimuli. Significant ( $p < 0.05$ ) topographic modulations are marked with black vertical bars and only those appearing for at least 10 ms are shown. The dot-outlined boxes indicate the POIs determined based on results of peak analysis, waveform  $t$ -tests and TANOVAs for further investigations of topographic pattern differences.

## TANOVAs for LF presentations

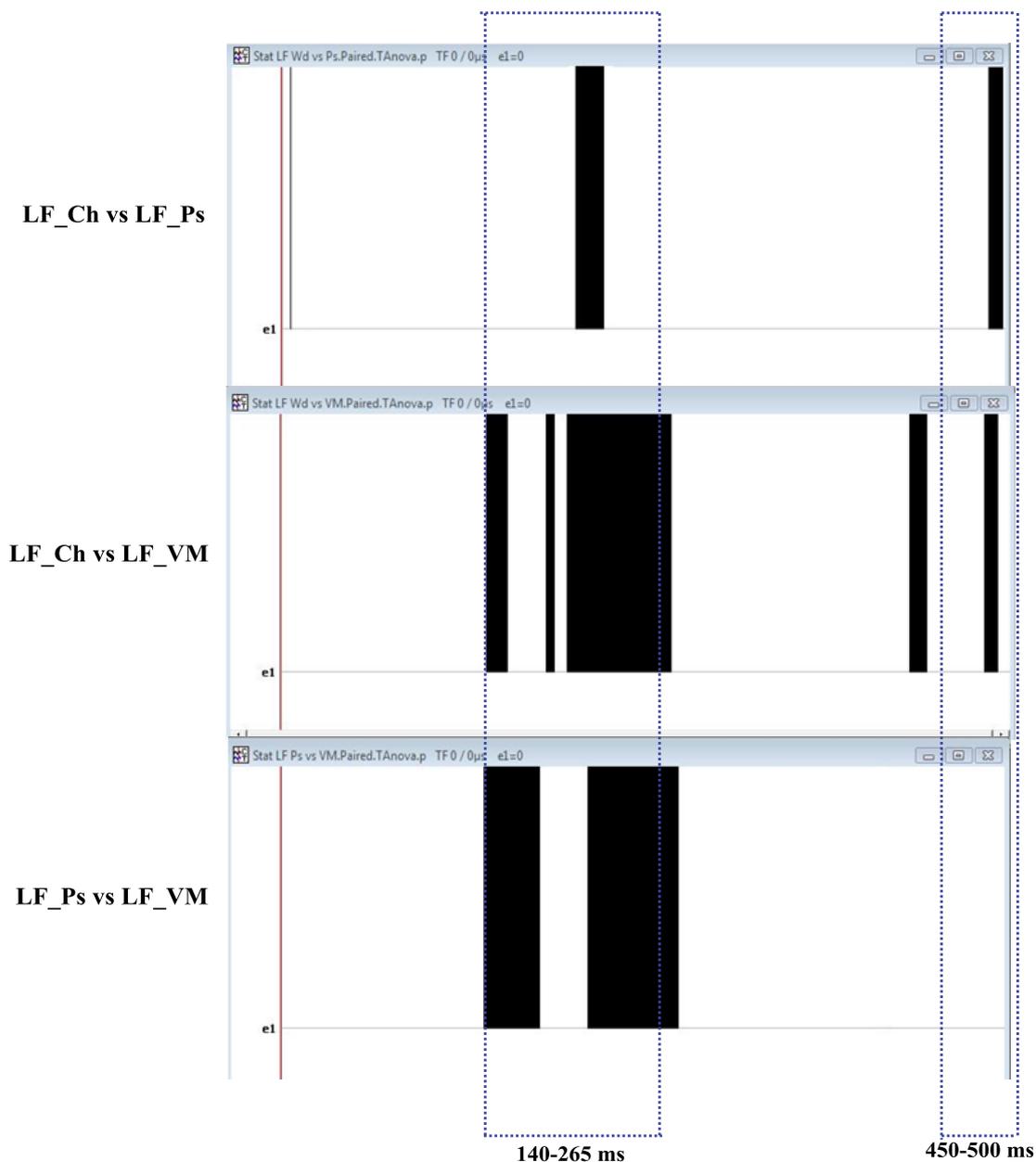


Figure 7.7-B. Results of point-wise TANOVAs between LF conditions. The top panel shows the results of TANOVA comparisons between the LF\_Ch and LF\_Ps stimuli, the middle panel the LF\_Ch and LF\_VM stimuli, and the bottom panel the LF\_Ps and LF\_VM stimuli. Significant ( $p < 0.05$ ) topographic modulations are marked with black vertical bars and only those appearing for at least 10 ms are shown. The dot-outlined boxes indicate the POIs determined based on results of peak analysis, waveform  $t$ -tests and TANOVAs for further investigations of topographic pattern differences.

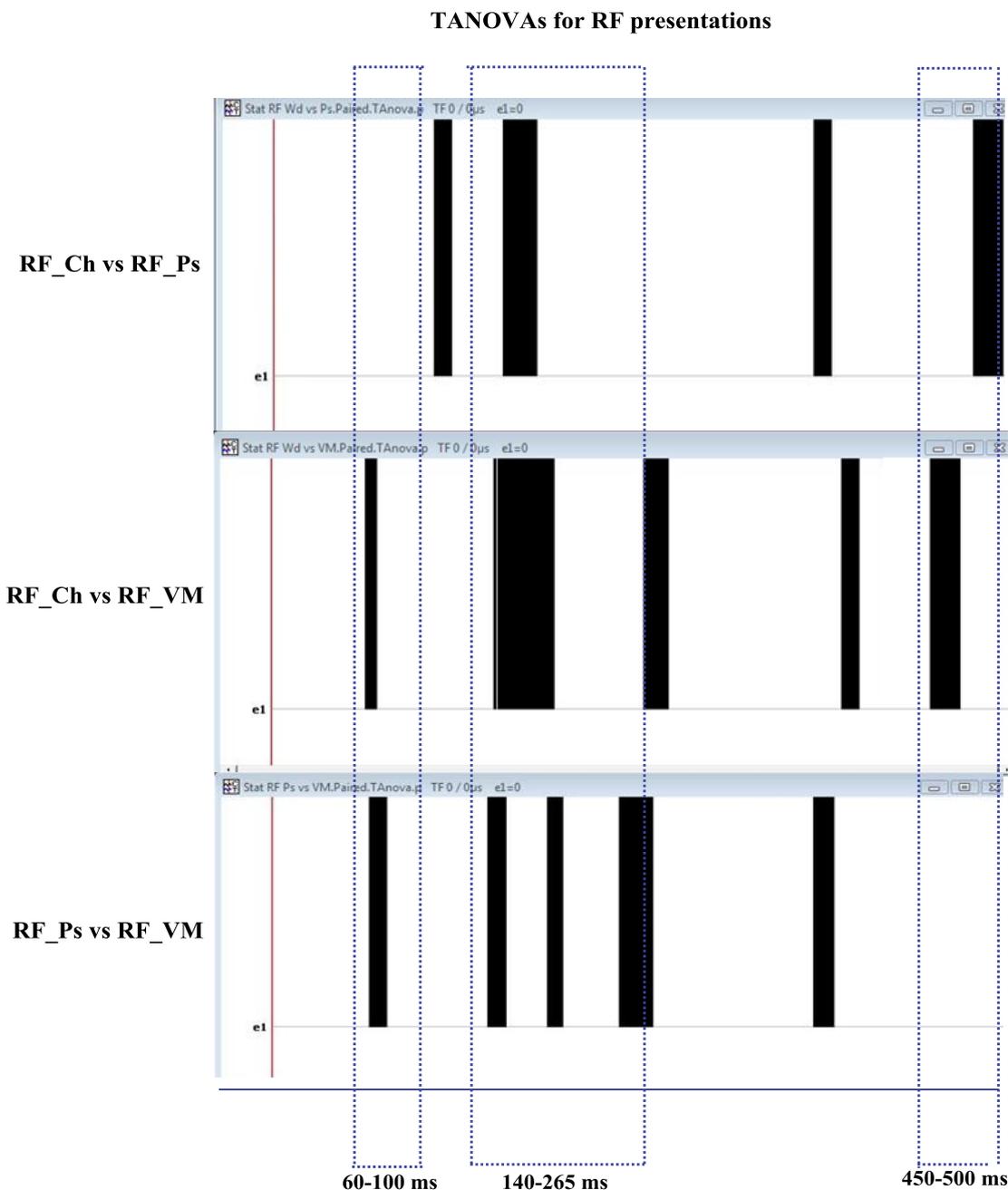


Figure 7.7-C. Results of point-wise TANOVAs between LF conditions. The top panel shows the results of TANOVA comparisons between the RF\_Ch and RF\_Ps stimuli, the middle panel the RF\_Ch and RF\_VM stimuli, and the bottom panel the RF\_Ps and RF\_VM stimuli. Significant ( $p < 0.05$ ) topographic modulations are marked with black vertical bars and only those appearing for at least 10 ms are shown. The dot-outlined boxes indicate the POIs determined based on results of peak analysis, waveform  $t$ -tests and TANOVAs for further investigations of topographic pattern differences.

## TANOVAs for RX presentations

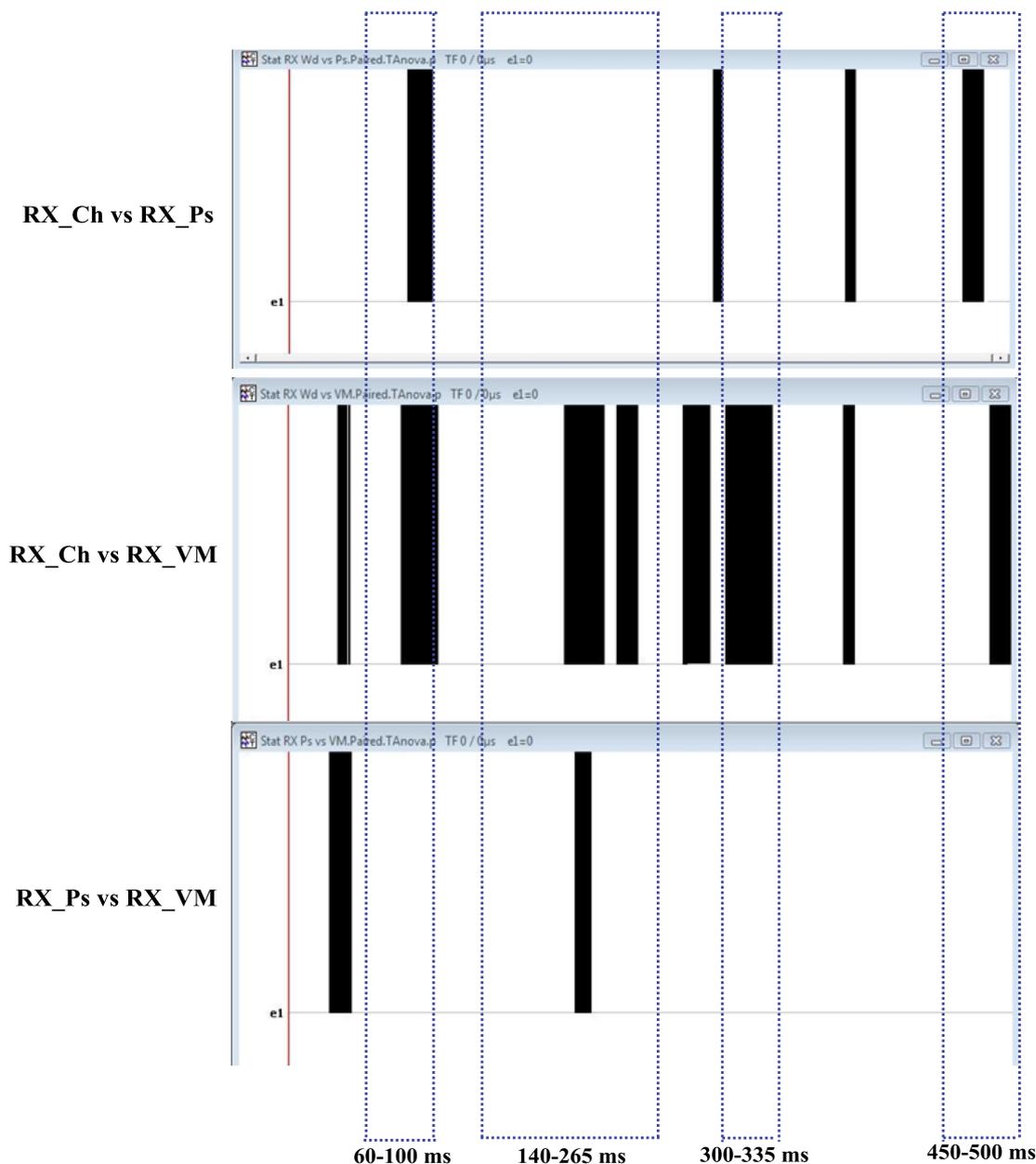


Figure 7.7-D. Results of point-wise TANOVAs between RX conditions. The top panel shows the results of TANOVA comparisons between the RX\_Ch and RX\_Ps stimuli, the middle panel the RX\_Ch and RX\_VM stimuli, and the bottom panel the RX\_Ps and RX\_VM stimuli. Significant ( $p < 0.05$ ) topographic modulations are marked with black vertical bars and only those appearing for at least 10 ms are shown. The dot-outlined boxes indicate the POIs determined based on results of peak analysis, waveform  $t$ -tests and TANOVAs for further investigations of topographic pattern differences.

#### 7.4.2.3 Results of GFP t-tests

The time course of ERP response modulations has just been examined at the individual-electrode level. Identical point-wise paired t-tests were conducted on the GFP data and the results showed no significant electric field strength modulations caused by different stimuli presented in a particular location.

#### 7.4.2.4 Results of TANOVA's

Global dissimilarity (refer back to relevant explanations in Section 7.3.7) was calculated between different stimuli types across presentation locations to test whether the ERP waveform differences identified earlier were due to topographic modulations, which would indicate changes in the underlying generator configuration. Results of these TANOVA's are shown in Figure 7.7. Topographic modulations first appeared at ~ 30 ms for comparisons between RX\_Ps and RX\_VM and then largely fell into the four periods (60-100 ms, 140-265 ms, 300-335 ms and 450-500 ms) in which waveform modulations were observed in the preceding step of analysis. Since point-wise comparisons between stimulus types across presentation locations at the individual electrode level (as in the preceding step) and at the global topographic level (as in the current step) suggested similar periods of response modulations, these four periods were determined as periods of interest (POI, in a similar vein to the notion of 'ROI' in fMRI studies) for further analyses.

#### 7.4.2.5 Results of Topographic pattern analyses

Results of previous steps of analyses helped to determine the POIs for further investigations of topographic pattern differences. As indicated by the dot-outlined boxes in Figures 7.5, 7.6 and 7.7, they were 60-100 ms (corresponding to the contralateral P1 component), 140-265 ms (covering the ipsilateral P1, the contralateral and ipsilateral N1 and the P2), 300-335 ms (corresponding to the P3) and 450-500 ms (the primitive stage

of the N400). The aim of the topographic pattern analysis was to determine whether topographic differences observed above were explainable by a single or multiple configuration changes or alternatively by a latency shift across conditions.

### **POI of 60-100 ms**

For the POI of 60-100 ms, four topographic microstates were identified in the group-averaged ERPs from all the twelve experimental conditions. Figure 7.8 shows the group-averaged segmentation output and the four template maps within this period. A four-way repeated measures ANOVA (Map\*Eccentricity\*VisField\*Stimulus) conducted on map NumTF (overall duration of the map, refer back to Table 7.1) statistically confirmed the segmentation results that distinct maps dominated the experiment conditions. Specifically, a two-way interaction of VisField\*Map ( $F_{(3,7)} = 18.22, p < .001, \eta_{\{p\}}^2 = .70$ ) showed that Maps 1 and 3 occurred more frequently for LVF conditions (15.9 and 19.7 ms, respectively,  $ps < .05$ ) while Maps 2 and 4 for RVF conditions (12.1 and 22.0 ms, respectively,  $ps < .05$ ). Two three-way interactions, Map\*Eccentricity\*VisField ( $F_{(3,7)} = 4.06, p < .05, \eta_{\{p\}}^2 = .34$ ) and Map\*VisField\*Stimulus ( $F_{(6,7)} = 2.78, p < .05, \eta_{\{p\}}^2 = .27$ ) further revealed that Map 1 was most representative of the topographic configuration over 60-100 ms for the LX presentations while Map 3 for LF presentations; Map 2 best described the topographies for RX\_Ps and RX\_VM presentations while Map 4 for RF\_Ps, RF\_VM and RVF\_Ch, both foveal and extrafovea, presentations ( $ps < .05$ ).

To further test whether the functional microstates under each condition, as indicated by the template maps, differed in terms of their onsets, offsets, MaxGFP, MeanGFP and TFMaxGFP (refer back to Table 7.1 for explanation), these measures of the dominant map under each condition were submitted to separate three-way ANOVAs (Eccentricity\*VisField\*Stimulus). No significant effects were found for the temporal

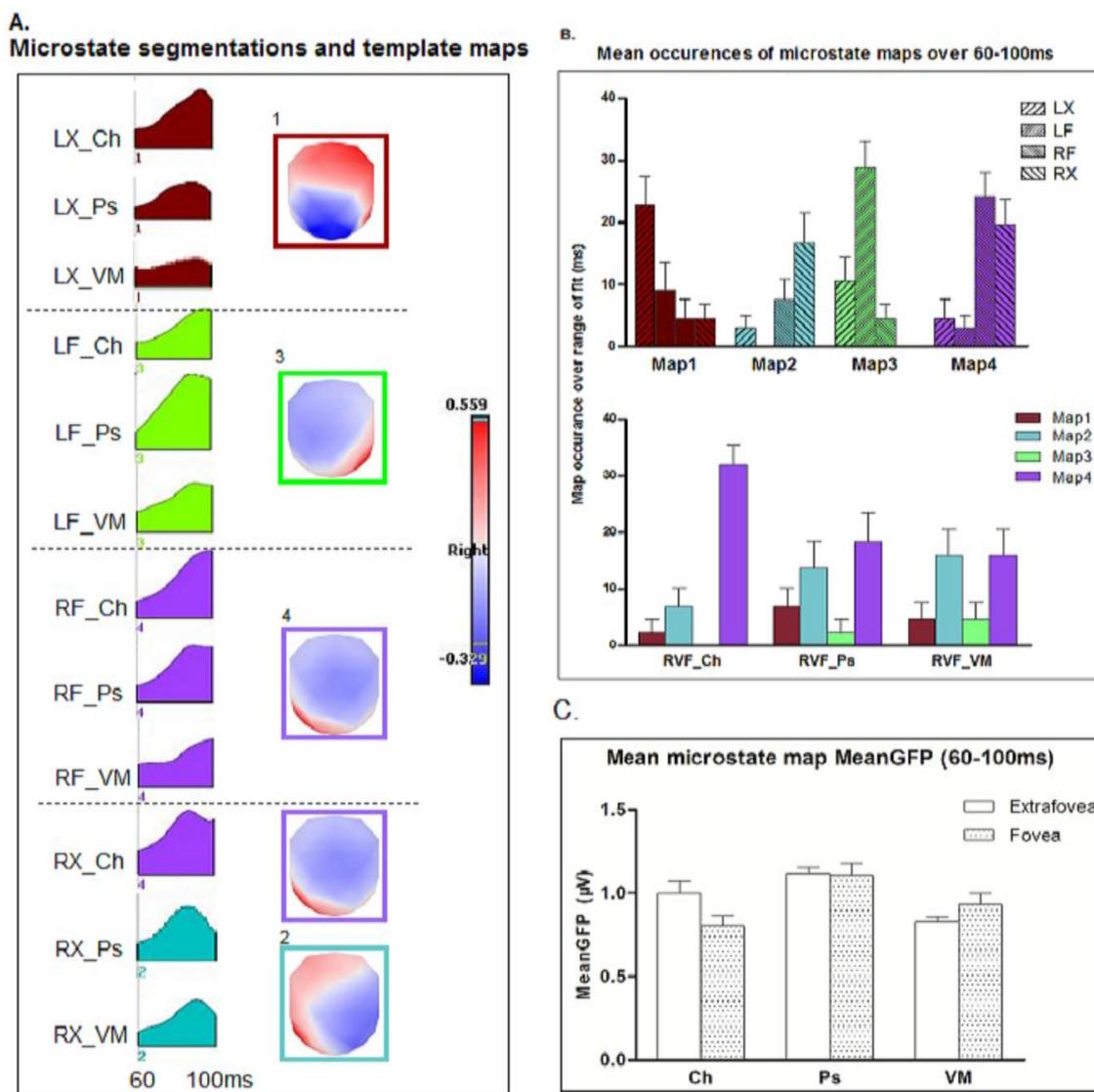


Figure 7.8. Results of the topographic pattern analysis for the POI of 60-100ms. (A) The four microstates identified by group-averaged segmentation are shown on the left and their template maps framed in corresponding colours on the right. (B) The reliability of group-averaged segmentations was tested at the individual subject level by performing a four-way ANOVA on the occurrence frequency (in ms) of each template map across conditions in the fitting procedure. The top portion depicts a Map\*Eccentricity\*VisField interaction which revealed that Map 1 was most frequent for LX presentations, Map 3 for LF presentations, Map 4 for RF presentations, and Map 2 for RX presentations. The bottom portion depicts a Map\*VisField\*Stimulus interaction which further established that Map 4 dominated the RVF\_Ch topographies irrespective of eccentricity. These effects confirmed the observations in group-averaged segmentations. (C) Mean MeanGFP of the topographic microstate across stimulus conditions at either eccentricity.

measures, i.e., onset, offset and TFMaxGFP. A main effect of stimulus was found for MeanGFP ( $F_{(2,7)} = 14.19, p < .01, \eta_p^2 = .64$ ) with the topographies in response to Ps stimuli exhibiting greater overall strength than those to Ch and VM stimuli (1.11 vs 0.90 vs 0.88  $\eta V, ps < .01$ ). An additional interaction between stimulus and eccentricity was also observed for MeanGFP over 60-100 ms ( $F_{(2,7)} = 3.45, p < .05, \eta_p^2 = .31$ ). Specifically, the overall MeanGFP of topographic maps under extrafoveally-presented Ch conditions was greater than that under foveally-presented Ch conditions (1.00 vs 0.80  $\eta V, p < .01$ ), as shown in Figure 7.8. It is also worth noting that the MaxGFP data exhibited a similar stimulus difference ( $p = 0.06$ ) with greater MaxGFP for Ps maps than for VM maps.

#### **POI of 140-265 ms**

For the POI of 140-265 ms, ten topographic microstates were identified in the group-averaged ERPs from all the twelve experimental conditions. Figure 7.9 shows the segmentation output and the ten template maps within this POI under each experimental condition in their temporal sequences. The present study was interested in what topographic patterns emerged under the Ch conditions and whether the Ps and VM conditions showed same patterns. Visual inspection of the group-averaged segmentation output found that the topographic configuration changes under the character conditions during this POI were mainly characterized by a four-map sequence differentiating between visual fields. Specifically, the LF\_Ch conditions featured a map sequence of 1-4-6-5 while the RF\_Ch conditions 2-3-5-6. The LX\_Ch and the RX\_Ch conditions shared the same four-map sequence as in the LF\_Ch and the RF\_Ch respectively with an additional map segment at the end (Map 7 under the LX\_Ch condition and Map 5 under RX\_Ch). The Ps conditions exhibited the same map sequences as the Ch conditions except that the RX\_Ps did not contain the additional map segment. Greater

variations were observed under the VM conditions. Although the LVF\_VM and the RVF\_VM conditions also showed the same map sequences of 1-4-6-5 and 2-3-5-6 respectively, they also contained map segments which were not present in the Ch and Ps conditions, i.e., Maps 8, 9 and 10.

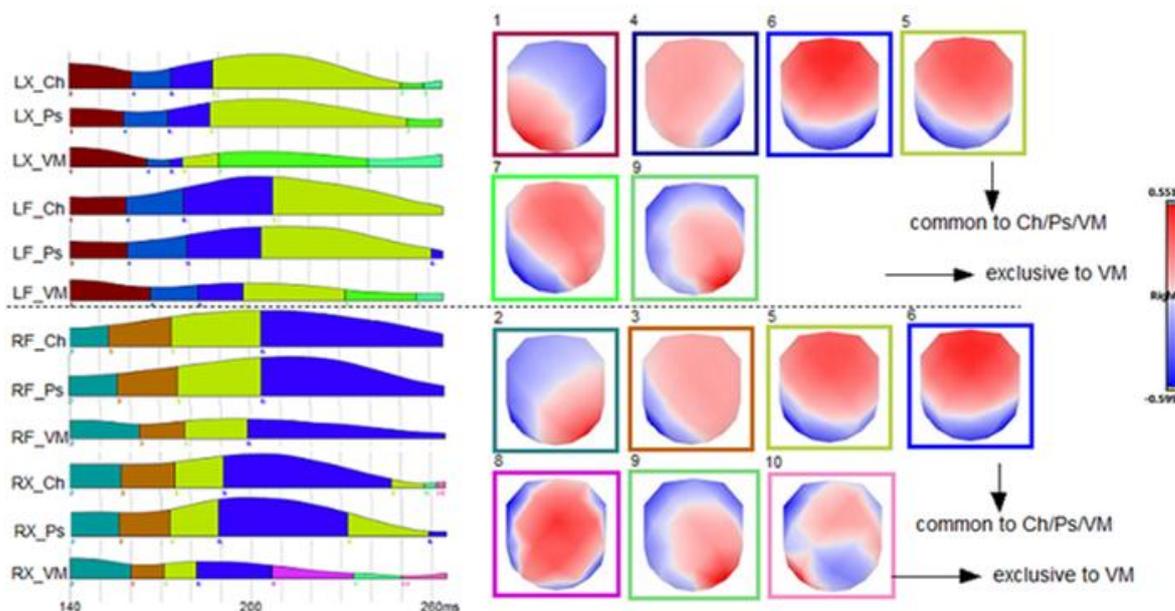


Figure 7.9. Output of the group-averaged topographic pattern segmentation for the POI of 140-265 ms and the ten template maps.

The functional microstates represented by Maps 1 and 2, which featured a positivity in the left and the right parietal-occipital areas respectively, corresponded well with the Ipsilateral P1 (IpsiP1) component for the LVF and the RVF stimuli. A four-way repeated measures ANOVA (Map\*Eccentricity\*VisField\*Stimulus) conducted on the NumTF data of Map 1 and Map 2 under each of the twelve experimental conditions found an interaction between Map and VisField ( $F_{(1,7)} = 12.97$ ,  $p < .05$ ,  $\eta^2 = .62$ ) which statistically confirmed that Map 1 represented the IpsiP1 topography for LVF stimuli and Map 2 the RVF stimuli ( $ps < .05$ ), as shown in Figure 7.10. In addition, there was a main effect of Map ( $F_{(1,7)} = 5.07$ ,  $p < .05$ ,  $\eta^2 = .40$ ) with Map 1 lasting longer period than Map 2 (13 vs 10 ms). Separate three-way (Eccentricity\*VisField\*Stimulus) ANOVAs were then conducted on the onset, offset,

TFMaxGFP, MaxGFP and MeanGFP of the IpsiP1 topography across conditions. A main effect of visual field was found for both onset ( $F_{(1,7)} = 9.69, p < .01, \eta^2 = .55$ ) and TFMaxGFP ( $F_{(1,7)} = 4.31, p < .05, \eta^2 = .37$ ) with the LVF map (Map 1) started and reached its maximum GFP at an earlier point of time than the RVF map (Map 2) (approximately 140 vs 144 ms, and 145 vs 148 ms, respectively,  $ps < .05$ ), as indicated by the numbering of maps in their temporal sequence. No significant effect was found in the offset, MaxGFP or MeanGFP data.

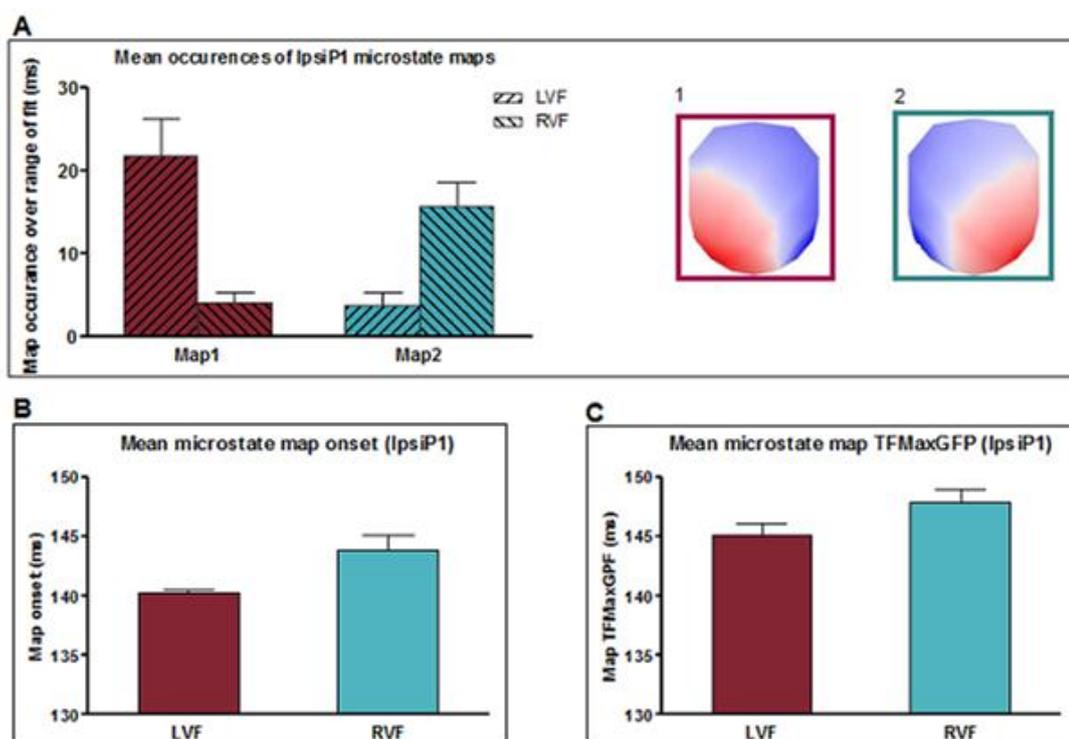


Figure 7.10. Results of the fitting procedure for the microstate of IpsiP1 (~ 140-160 ms). (A) The reliability of group-averaged segmentations (see segments corresponding to Map 1 and Map 2 in Figure 7.9) was tested at the individual subject level by performing a four-way ANOVA on the occurrence frequency (in ms) of Map 1 and Map 2 across conditions. The graph on the left plots a Map\* VisField interaction which confirmed that Map 1 was more representative of the IpsiP1 topography for LVF presentations while Map 2 for RVF presentations. The two template maps are shown on the right. (B) A three-way ANOVA performed on the onset of the dominant IpsiP1 map under each condition revealed a main effect of visual field with the LVF conditions showing earlier map onsets than the RVF conditions. (C) A three-way ANOVA performed on the TFMaxGFP of the dominant IpsiP1 map under each condition revealed a main effect of visual field with the LVF conditions showing earlier map TFMaxGFPs than the RVF conditions.

Maps 3 and 4 were characterized by a prominent negativity in the left and the right temporal-occipital areas respectively and represented the scalp topography of Contralateral N1 (ContraN1) for the RVF and the LVF stimuli respectively. The same set of ANOVAs described above were performed for Maps 3 and 4 after the fitting procedure. The four-way ANOVA on NumTF found an interaction between Map and VisField ( $F_{(1,7)} = 22.66$ ,  $p < .01$ ,  $\eta^2 = .74$ ) which confirmed that Map 4 was most representative of the LVF conditions and Map 3 the RVF conditions ( $ps < .01$ ), as shown in Figure 7.11. Tests on the other three temporal measures found no significant differences. A main effect of stimulus was observed for both MaxGFP ( $F_{(2,7)} = 4.44$ ,  $p < .05$ ,  $\eta^2 = .36$ ) and MeanGFP ( $F_{(2,7)} = 4.66$ ,  $p < .05$ ,  $\eta^2 = .37$ ) with the VM maps showing lesser strength than the Ch and Ps maps (MaxGFP: 1.7 vs 2.2 vs 2.3  $\eta$ V; MeanGFP: 1.5 vs 1.8 vs 1.9  $\eta$ V;  $ps < .05$ ), which are plotted in Figure 7.12.

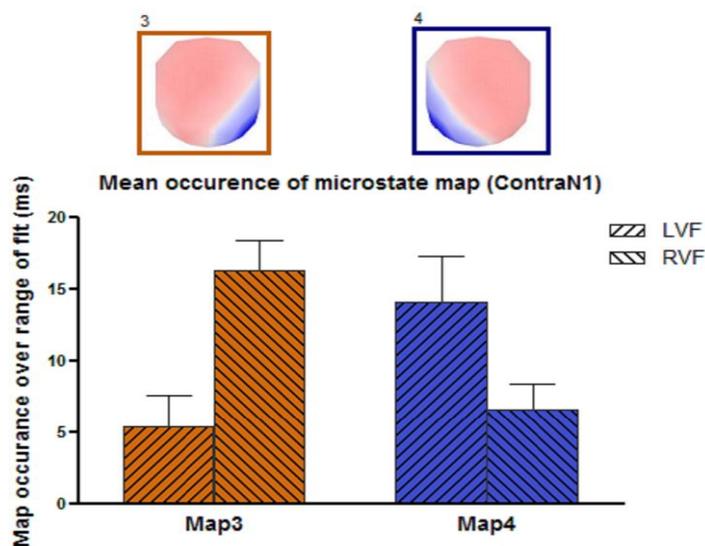


Figure 7.11. Results of the fitting procedure on map occurrence frequency for the microstate of ContraN1 ( $\sim 160$ - $180$  ms). The reliability of group-averaged segmentations (see segments corresponding to Map 3 and Map 4 in Figure 7.9) was tested at the individual subject level by performing a four-way ANOVA on the occurrence frequency (in ms) of Map 3 and Map 4 across conditions. The graph plots a Map\* VisField interaction which confirmed that Map 4 was more representative of the IpsiP1 topography for LVF presentations while Map 3 for RVF presentations. The two template maps are shown on the top.

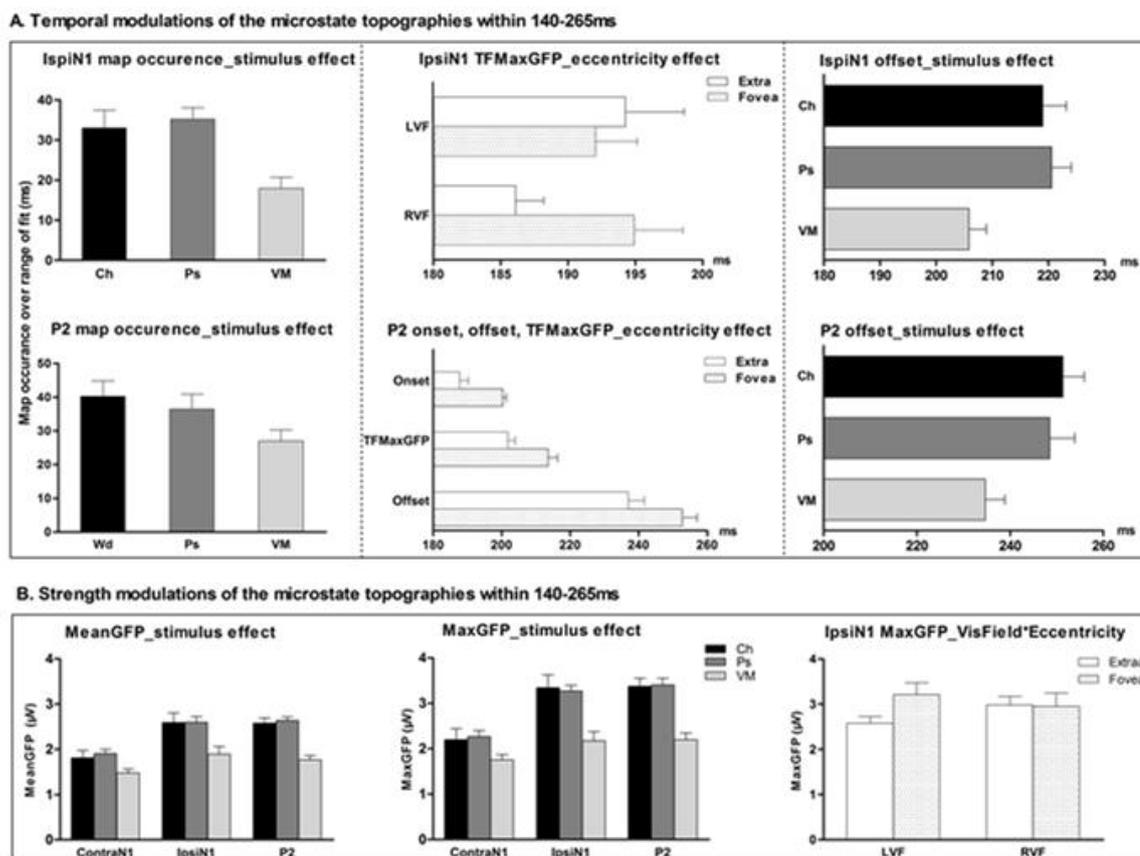


Figure 7.12. Results of the analyses of temporal and strength measures of the microstate topographies within 140-265 ms. (A) Temporal modulations of the microstate topographies within 140-265 ms. The column on the left, from top to bottom, shows that the overall durations of IpsiN1 and P2 topographies in response to VMs were significantly shorter than those in response to characters and pseudocharacters. The column in the middle, from top to bottom, shows that the IpsiN1 topographies had earlier TFMxGFP for RX than for RF presentations and the P2 topographies for extrafoveal presentations had earlier onset, offset and TFMxGFP times than those for foveal presentations. The column on the right, from top to bottom, shows that the IpsiN1 and P2 topographies had earlier offsets in response to VMs compared to characters and pseudocharacters. (B) Strength modulations of the microstate topographies within 140-265 ms. The graph on the left and the graph in the middle show that characters and pseudocharacters elicited greater MaxGFP and MeanGFP than VMs throughout the microstates of ContraN1, IpsiN1 and P2. The graph on the right shows that the MaxGFP of the IpsiN1 topography under the RX conditions was in general greater than that under the LX conditions; also, LF conditions showed greater MaxGFP of IpsiN1 topography than LX conditions.

Map 5 and Map 6 appeared in the topography sequences for the LVF and the RVF stimuli in reversed order as representing the IpsiN1 (180-200 ms) and the P2 (~200-250 ms), respectively. Since the present study was not interested in comparing the durations of topographic patterns representing distinct microstates within the same condition, across-condition comparisons on the NumTF data of Maps 5 and 6 were performed, instead by using two three-way ANOVAs, which found a main effect of stimulus for both microstates and a main effect of eccentricity for the P2 microstate only. Specifically, the IpsiN1 and the P2 topographies lasted longer for characters and pseudocharacters compared to VMs (IpsiN1:  $F_{(2,7)} = 15.6$ ,  $p < .001$ ,  $\eta^2 = .67$ ; P2:  $F_{(2,7)} = 5.25$ ,  $p < .05$ ,  $\eta^2 = .40$ ; all  $ps < .05$ )

Identical three-way ANOVAs were conducted on the other measures of Maps 5 and 6. No significant difference was found for IpsiN1 map onset across conditions while a main effect of stimulus showed that the IpsiN1 maps for VM conditions had early offsets than those for the Ch and Ps conditions ( $F_{(2,7)} = 13.28$ ,  $p < .001$ ,  $\eta^2 = .62$ ) and an interaction between visual field and eccentricity ( $F_{(1,7)} = 5.43$ ,  $p < .05$ ,  $\eta^2 = .41$ ) showed delayed TFM<sub>MaxGFPs</sub> of IpsiN1 maps for foveal compared to extrafoveal presentations in the RVF ( $p < .05$ ). For the P2 maps, an eccentricity effect was observed for its onset ( $F_{(1,7)} = 29.72$ ,  $p < .001$ ,  $\eta^2 = .79$ ), offset ( $F_{(1,7)} = 34.31$ ,  $p < .001$ ,  $\eta^2 = .81$ ) and TFM<sub>MaxGPF</sub> ( $F_{(1,7)} = 26.76$ ,  $p < .01$ ,  $\eta^2 = .77$ ) which all showed a later latency for the foveal conditions compared to the extrafoveal conditions ( $ps < .05$ ). There was also a stimulus effect ( $F_{(2,7)} = 13.67$ ,  $p < .001$ ,  $\eta^2 = .28$ ) for the offset of the P2 maps with the Ch and Ps conditions exhibiting later P2 topography offsets than the VM conditions ( $p < .05$ ). In the respect of strength modulations, a stimulus effect on the MaxGFP ( $F_{(2,7)} = 29.15$ ,  $p < .001$ ,  $\eta^2 = .79$ ;  $F_{(2,7)} = 34.48$ ,  $p < .001$ ,  $\eta^2 = .81$ ) and the MeanGFP ( $F_{(2,7)} = 23.22$ ,  $p < .001$ ,

$\eta^2 = .74$ ;  $F_{(2,7)} = 31.84$ ,  $p < .001$ ,  $\eta^2 = .80$ ) was found common to the IpsiN1 and the P2 topographies. with the Ch and Ps conditions showing greater global strength than the VM conditions ( $ps < .01$ ). Moreover, there was an interaction between eccentricity and visual field for the MaxGFP of the IpsiN1 topography ( $F_{(1,7)} = 31.88$ ,  $p < .001$ ,  $\eta^2 = .80$ ). The MaxGFP of the IpsiN1 topography under the RX conditions was in general greater than that under the LX conditions; also, LF conditions showed greater MaxGFP of IpsiN1 topography than LX conditions ( $ps < .05$ ). It is worth noting that the same interaction effect was close to significance ( $p < .07$ ) in the MeanGPF of IpsiN1 topography. These results are also plotted in Figure 7.12.

### **POI of 300-335 ms**

For the POI of 300-335 ms, group-averaged segmentation found four template maps in total across conditions. Figure 7.13 shows the segmentation output and the four maps. A four-way repeated measures ANOVA (Map\*Eccentricity\*VisField \*Stimulus) conducted on the NumTF data found a Map\*VisField interaction ( $F_{(3,7)} = 5.86$ ,  $p < .01$ ,  $\eta^2 = .42$ ) and a Map\*Eccentricity\*VisField\*Stimulus interaction ( $F_{(6,7)} = 3.90$ ,  $p < .01$ ,  $\eta^2 = .33$ ). Post-hoc comparisons for the two-way interaction revealed that Map 1 was more frequently observed for LVF than for RVF presentations while Map 4 was more frequently observed for RVF than for LVF presentations. ( $ps < .05$ ). Post-hoc comparisons for the four-way interaction further determined that RX\_VM was best characterized by Map 3. Therefore, Map 1 for LVF presentations and Map 4 for RVF presentations except Map 3 for RX\_VM were used for further analysis of other temporal and strength measures obtained from the fitting procedure. Results of these further comparisons are plotted in Figure 7.14. Specifically, a main effect of stimulus was found in the onset ( $F_{(2,7)} = 7.30$ ,  $p < .01$ ,  $\eta^2 = .48$ ) and offset ( $F_{(2,7)} = 9.44$ ,  $p < .01$ ,  $\eta^2 = .54$ ) of the P3 microstate topography. Post-hoc tests revealed that

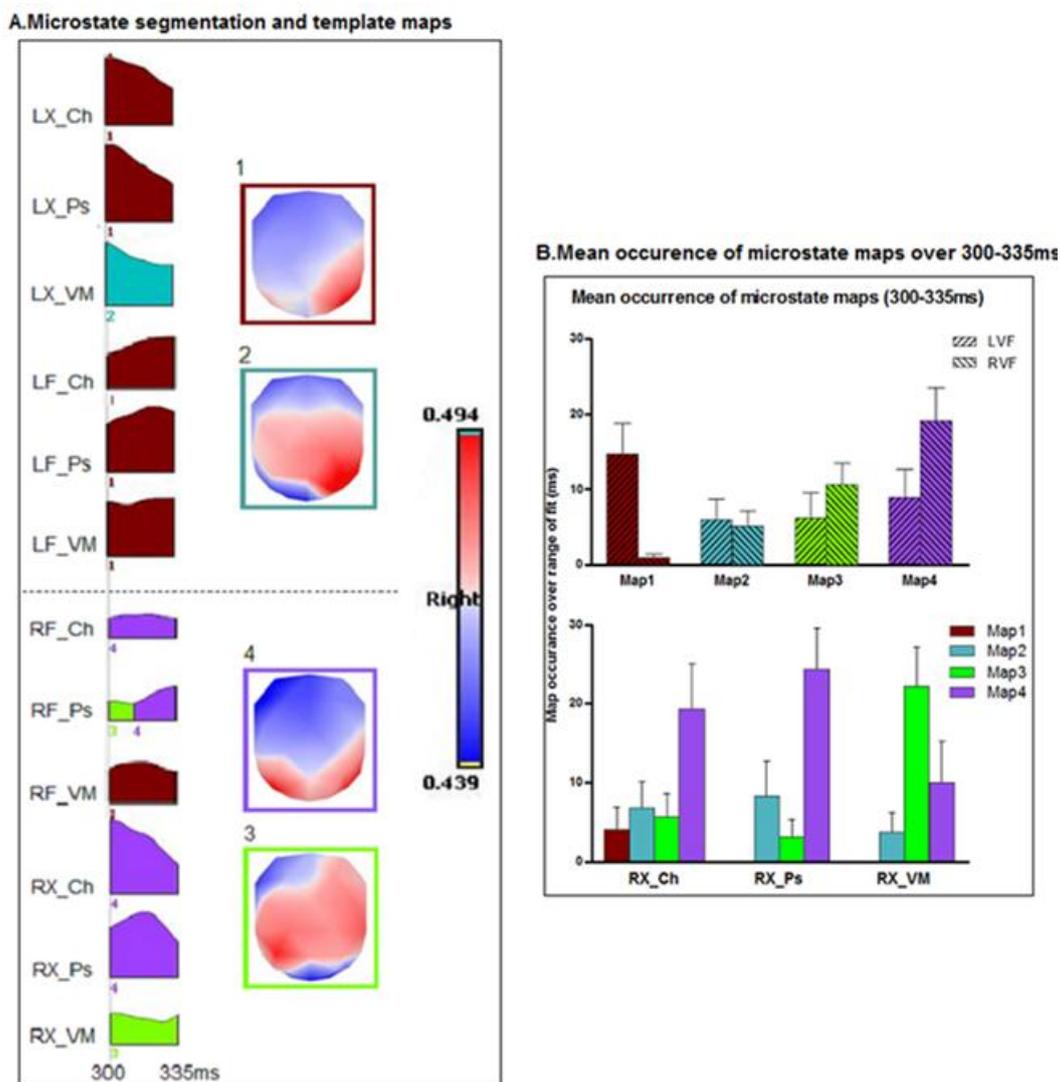


Figure 7.13. Results of the fitting procedure on map occurrence frequency for the POI of 300-335 ms. (A) The four microstates identified by group-averaged segmentation are shown on the left and their template maps framed in corresponding colours on the right. (B) The reliability of group-averaged segmentations was tested at the individual subject level by performing a four-way ANOVA on the occurrence frequency (in ms) of each template map across conditions in the fitting procedure. The top portion depicts a Map\*VisField interaction which revealed that Map 1 was more frequently observed for LVF than for RVF presentations while Map 4 was more frequently observed for RVF than for LVF presentations. The bottom portion depicts a Map\*Eccentricity\*VisField\*Stimulus interaction which further determined that the P3 topography in response to RX\_VM stimuli was best characterized by Map 3.

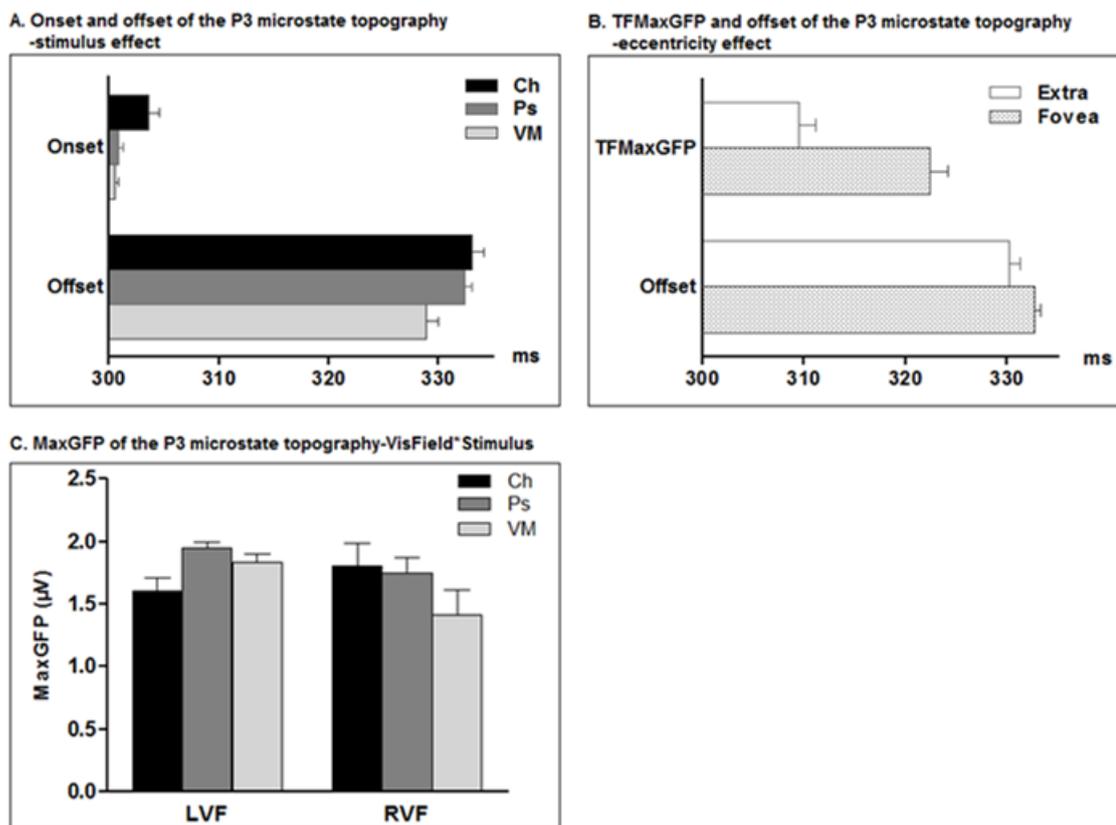


Figure 7.14. Results of the analyses of temporal and strength measures of the microstate topographies during the POI of 300-335 ms. (A) The onset and offset of the P3 microstate topography were significantly affected by stimulus type. The P3 topography started at a later point of time for characters compared to pseudocharacters and VMs and ended at a later point of time for characters and pseudocharacters relative to VMs. (B) The TFMxGFP and offset of the P3 microstate topography were significantly affected by eccentricity. The P3 topography reached its maximum and ended at a later point of time for foveal presentations compared to extrafoveal presentations. (C) The MaxGFP of the P3 microstate topography was affected by a VisField\*Stimulus interaction. When presented in the LVF, pseudocharacters elicited greater MaxGFP relative to characters.

the P3 microstate topography started at a later point of time for characters compared to pseudocharacters and VMs and ended at a later point of time for characters and pseudocharacters relative to VMs ( $p < .05$ ). A additional main effect of eccentricity was found in the TFMxGFP ( $F_{(1,7)} = 25.41, p < .01, \eta^2 = .76$ ) and the offset ( $F_{(1,7)} = 8.92, p < .05, \eta^2 = .53$ ) of the P3 topography with them being delayed for foveal presentations compared to extrafoveal presentations. At the respect of strength modulations, an interaction between visual field and stimulus was found in the MaxGFP

( $F_{(2,7)} = 7.83, p < .01, \eta^2 = .49$ ). Post-hoc tests showed that the P3 topographic MaxGFP significantly increased for pseudocharacters compared to characters when they were presented in the LVF ( $p < .05$ ).

### POI of 450-500 ms

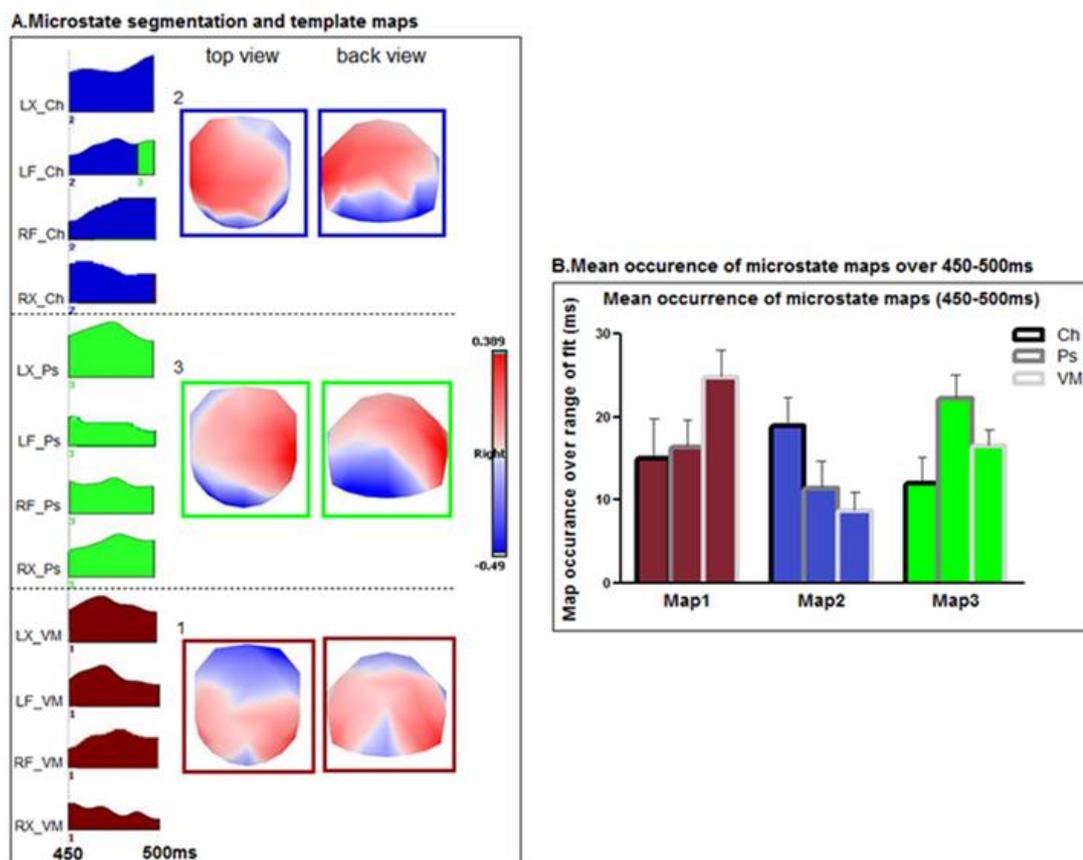


Figure 7.15. Results of the fitting procedure on map occurrence frequency for the POI of 450-500 ms. (A) The three microstates identified by group-averaged segmentation are shown on the left and their template maps framed in corresponding colours on the right. (B) The reliability of group-averaged segmentations was tested at the individual subject level by performing a four-way ANOVA on the occurrence frequency (in ms) of each template map conditions in the fitting procedure. A Map\*Stimulus interaction effect revealed that Maps 2 and 3 were more frequently observed for characters and pseudocharacters respectively while Map 1 best described the microstate topography during this POI for VMs.

For the POI of 450-500 ms, group-averaged segmentation found three template maps. Figure 7.15 shows the segmentation output and the three template maps. A four-way ANOVA conducted on the NumTF data only found an interaction between Map

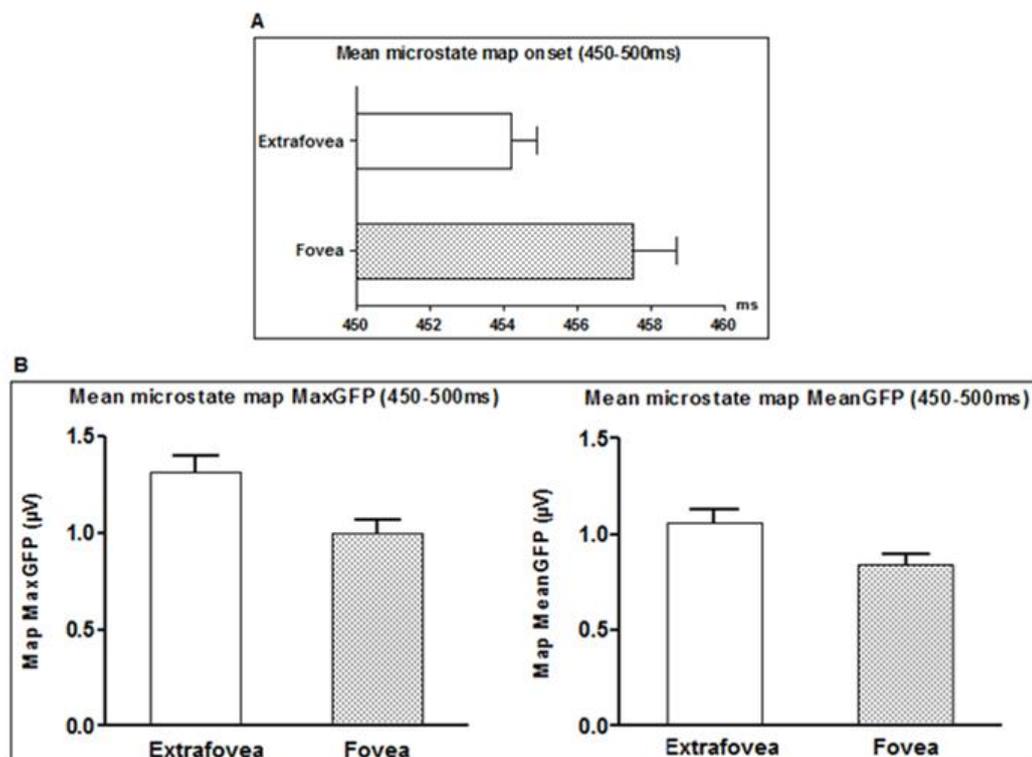


Figure 7.16. Results of the analyses of temporal and strength measures of the microstate topographies during the POI of 450-500 ms. (A) The onset of the (primitive) N400 microstate topography was significantly affected by eccentricity with extrafoveal presentations showing earlier onset relative to extrafoveal presentations. (B) The MaxGFP and MeanGFP of the (primitive) N400 microstate topography were affected by eccentricity with extrafoveal presentations showing greater topographic strength than foveal presentations.

and Stimulus ( $F_{(4,7)} = 3.32, p < .05, \eta^2 = .29$ ) which confirmed that a distinct map was more often observed for each of the three stimulus conditions, regardless of visual field and eccentricity. Among the temporal measures of these maps, only the onset but not the offset or TfMaxGFP were compared across conditions. A main effect of eccentricity ( $F_{(1,7)} = 6.06, p < .05, \eta^2 = .43$ ) showed that the onset of the N400 topography for the foveal conditions was later than that for the extrafoveal conditions. This latency shift was well reflected in the ERP waveforms wherein N400 peaks showed through under the extrafoveal conditions while no N400 peaks were visible under the foveal conditions yet. In the respect of strength modulations, significant eccentricity effects were found in the MaxGFP ( $F_{(1,7)} = 11.39, p < .01, \eta^2 = .59$ )

and MeanGFP ( $F_{(1,7)} = 10.70$ ,  $p < .01$ ,  $\eta^2 = .57$ ) which were both weaker for the foveal presentations relative to the extrafoveal presentations. It is also worth noting that a stimulus effect approached significance in the MaxGFP ( $p = .06$ ) and the MeanGFP ( $p = .07$ ), both being larger for characters than for pseudocharacters. These results are plotted in Figure 7.16.

### **Summary**

The topographic pattern analysis was performed within the four POIs of topographic differences established in the previous steps. As noted earlier, these four POIs largely corresponded with the ERP components identified in the peak analysis. Specifically, the POI of 60-100 ms corresponded with the ContraP1 for foveal presentations (and the C1 for extrafoveal presentations; refer back to results for the POI of 60-100 above for details), the POI of 140-265 ms with the IpsiP1, the ContraN1, the IpsiN1 and the P2, the POI of 300-335 ms with the P3, and finally the POI of 450-500 ms with the rising N400.

The topographic microstate maps established in this step confirmed the split pattern of ERP peak latencies observed in the peak analysis. Indeed, for the microstates of ContraP1, IpsiP1, ContraN1, IpsiN1, and P3, topographic maps in response to presentations in either visual field were in the opposite direction to maps for the other visual field in terms of the activated hemisphere.

Topographic configuration within a particular microstate was not only affected by the visual field of stimuli but also by the lexicality and the eccentricity of stimuli. To be more specific, the topographic map for the RX\_Ch condition during the POI of 60-100 ms differed from that for the RX\_Ps and the RX\_VM conditions. This difference was due to a latency shift in that the topographic configuration for the RX\_Ch condition was synchronized with its foveal counterpart, temporally ahead of the topographic maps

under the RX\_Ps and the RX\_VM conditions (refer back to Figure 7.8). Such VisField\*Eccentricity\*Stimulus interaction was again found for the POI of 300-335 ms in which the scalp configuration in response to the RX\_VM conditions was distinct from that in response to the RX\_Ch and the RX\_Ps conditions (refer back to Figure 7.13). Finally, topographic configuration differences were observed within the POI of 450-500 ms. It is crucial to point out that at this stage the visuoperceptual influence, namely, the visual field and the eccentricity of presentation, was completely absent with characters, pseudocharacters and VMs each eliciting a distinct topographic pattern (refer back to Figure 7.15).

#### 7.4.2.6 Results of source estimations

Results of the above local peak and global topographic analyses showed that characters differed from pseudocharacters and VMs in either (local or global) or both respects throughout the 0-500 ms EEG segmentation. Therefore, the sLORETA was performed comparing characters versus pseudocharacters or VMs for each of these pairs of local or global ERP differences to find out if these scalp variations can be associated with certain modulations in the source generators and the results are shown in Figure 7.17.

The sLORETA results identified the brain areas that were responsible for the following pairs of scalp differences. Specifically, scalp configuration differences found between RX\_Ch versus RX\_Ps and RX\_VM during the POI of 60-100 ms were explained by a source located in the left middle occipital gyrus (BA19, MNI coordinates  $x, y, z = -40, -85, 10$ ) and a source in the left lingual gyrus (BA18, MNI coordinates  $x, y, z = -10, -100, -10$ ), respectively. In both cases activation was weaker in response to Ch stimuli than to Ps. For the P2 time window of 200-250 ms, sLORETA permutation results were significant under two paired comparisons, which were LF\_Ch vs LF\_VM

and RF\_Ch vs RF\_Ch . Topographic differences associated with these two paired comparisons could be explained by sources located in right medial frontal gyrus (BA 9, MNI coordinates  $x, y, z = 15, 25, 35$ ) and right superior frontal gyrus (BA9, MNI coordinates  $x, y, z = 40, 35, 40$ ) respectively. In both cases activation was stronger in response to Ch stimuli than to VM.

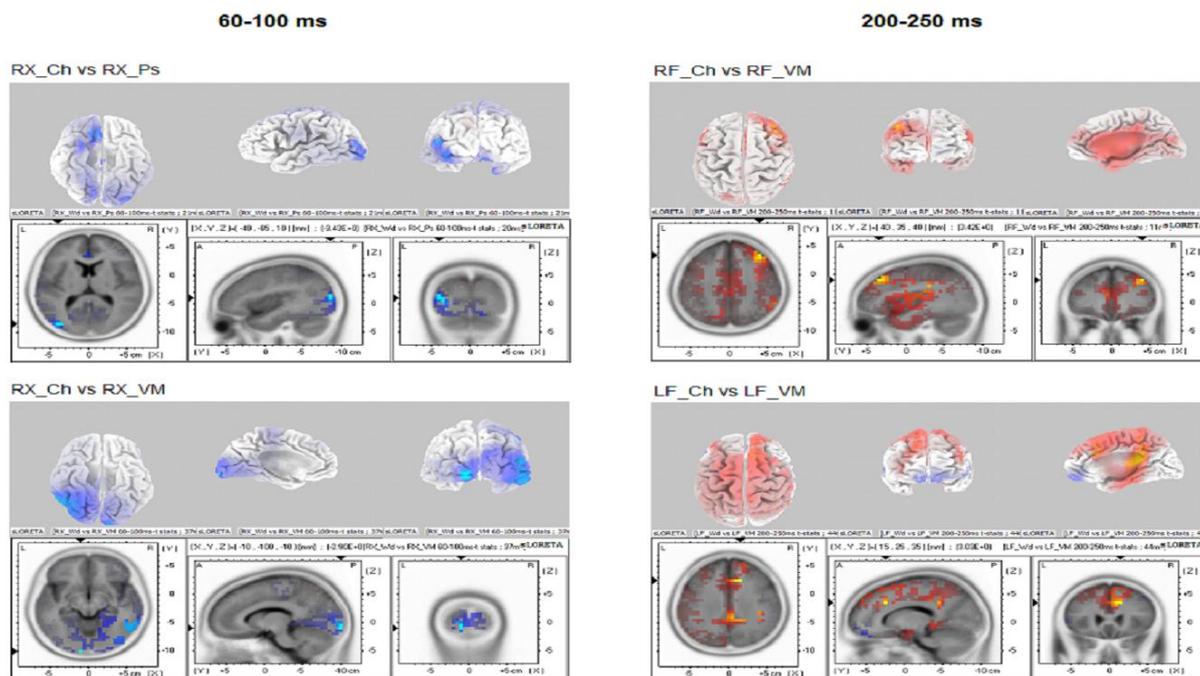


Figure 7.17. 3-D and head slice views of sLORETA differences.

## 7.5 Discussion

### 7.5.1 A micro view into the processes involved in individual ERPs

#### 7.5.1.1 C1, P1 and the topographic microstate of 60-160 ms

##### The temporal domain

C1 is the earliest identifiable human VEP reported in the literature with an onset latency around 50 ms and peak latency between 60 and 100 ms. C1 changes its polarity with the stimulated visual field and accordingly the activated part of the striate cortex.

In the current experiment, negative scalp responses were recorded for stimuli presented along the horizontal midline. This polarity agrees with the observations in many other studies (e.g., Clark, et al., 1995; Frey, Kelly, Lalor & Foxe, 2010; Proverbio & Adorni, 2009). Clark et al. (1995) showed that C1 remained negative in VEP waveforms until stimuli presented 15-20deg below the horizontal midline. It has been noted in the introduction of this chapter that the C1 wave usually shows fairly weak strength which makes the conventional peak analysis not an ideal procedure for statistical comparisons. The C1 peaks observed in the ERP waveforms here also showed weak strength with the foveal ones being slightly more visible than the extrafoveal ones. Following the previous studies, traditional peak analysis for C1 was not performed when it was difficult to determine the correct peaks (Vanni, Warnking, Dojat, Delon-Martin, Bullier & Segebarth, 2004; Ima, Gururajan, Zhang, Chen & He, 2007).

Concurrently with the midline C1, the early phase of P1 appears at more lateral sites in the hemisphere contralateral to the stimulated visual field. (Clark, Fan & Hillyard, 1995; Russo et al., 2001). In the present study, during the POI of 60-100 ms, this concurrence of C1 and (early contralateral) P1 was observed only for the RX\_Ps and RX\_VM stimuli. The topographic maps during this POI demonstrated that cortical responses to foveal stimuli had fully developed into the early contralateral P1 stage while the LX conditions were still in C1 stage, which was responsible for the difference in P1 peak latency between foveal and extrafoveal stimuli in the LVF. Unlike RX\_Ps and RX\_VM stimuli represented by a topographic map featuring concurrence of remaining C1 in the ipsilateral hemisphere and starting of early P1 in the contralateral hemisphere (over the more temporal sites), RX\_Ch stimuli during this period exhibited a topographic configuration synchronized to its foveal counterpart, namely, mature contralateral P1 activation in a broader occipito-temporal area reaching towards the

ipsilateral hemisphere.

These findings show an interaction between bottom-up visuo-anatomical constraints and top-down stimulus-specific influences in the temporal domain of ERP responses to characters and character-like stimuli as early as 60 ms. The visuo-perceptual influence of eccentricity on the temporal characteristics of brain activities at this stage can be accounted for by the visual anatomy of human retina. Specifically, the fovea part of the retina is characterized by a high concentration of cone photoreceptor cells which gradually become sparser towards the periphery where rod cells are more populated. There is evidence that cones respond to stimuli faster than rods (e.g., Kandel, Schwartz, Jessell, 2000). It is therefore reasonable to assume that foveal inputs that are sampled with more cones can reach the primary visual cortex more quickly than extrafoveal input. This delay is well demonstrated in the present study by the latency shift between the ContraP1 topography and consequently the overall P1 peaks in response to extrafoveal conditions relative to foveal conditions in the LVF. However this bottom-up visuo-anatomical effect of eccentricity can be modulated by the higher-order characteristics of stimuli. In particular, the synchronization of the ContraP1 topography and consequently the overall P1 peaks between the RX\_Ch and RF\_Ch conditions suggests that the visual pathway in the LH may be language-sensitive enough to speed up the relay of extrafoveal character information (2 degrees eccentricity) in the RVF from retina to the visual cortex as to 'catch up with' that of foveal (0.15 degrees eccentricity) character stimulation in the same visual field.

Immediately following the C1, the contralateral P1 for extrafoveal presentations appeared between 100-140 ms. Although no statistical analysis was performed for the topographic GFP measures during this time window, local peak latencies continued to be affected by the physical characteristics of stimuli including presentation visual field

and eccentricity. Although only a two-way interaction between these two factors was significant in the P1 latency, it is clear from the ERP waveforms that it was in the contralateral RH that P1 peaks for LX presentations were considerably delayed compared to LF presentations. This implies that further to the POI of 60-100 ms by the end of which period stimuli presented at both eccentricities had gone through the C1 activation, processing of extrafoveally presented Ps and VM stimuli was able to 'catch up with' that of their foveal counterparts only when they were projected from the RVF to the ipsilateral LH, as RX\_Ch had earlier on in the C1. In contrast, processing of extrafoveally presented stimuli in the LVF still lagged in the contralateral RH compared to their counterparts from the same visual field before this last trace of visuo-anatomical effect of eccentricity on ERP's latency eventually disappeared in the ipsilateral LH.

### **The strength domain**

Early top-down influences due to different stimulus types were evident in ERP strength measures both globally and locally. Specifically, comparisons of topographic MeanGFPs during the POI of 60-100 ms showed that pseudocharacters elicited greater activations than characters and VMs (MaxGFP differences close to significance level) and peak amplitude analysis exhibited the same pattern over the occipito-parietal area. Among the studies using legal English words and their illegal variations (pseudowords, nonwords, consonant strings, etc.), most of them reported that the earliest ERP difference between words and pseudowords occurred during the N1 time window (ranging from 150 to 200 ms depending on studies). In contrast, differences between English words and stimuli of non-linguistic categories, a visual categorization effect, was typically reported in the P1. For example, Rossion et al. (2003) reported larger P1 for faces and cars compared to words. Schendan, Ganis, & Kutas (1998) also found that occipital ERPs differentiated between words and other wordlike strings (nonwords and

pseudofont strings) versus faces and other objects during the P1 window but not between words and wordlike strings. The authors attributed this categorization effect to the visual dissimilarities, in particular in terms of low-level visual properties such as spatial frequency spectra or perhaps spatial dimensions, and concluded that neural operations have not become specialized for aspects of linguistic processing by the P1 stage.

The VM condition introduced in the present study made a more appropriate benchmark condition in that the VMs removed the lexicality of characters on the one hand while maintaining the overall spatial configuration and visual intensity (in terms of pixel number and luminance) of characters on the other hand. The observation of similar P1 amplitude in response to characters and VMs as contrasted to pseudocharacters may imply that it was the coarse-scale configurational information that the neural system extracts at the P1 stage to differentiate characters from pseudocharacters rather than the higher-order linguistic properties. This takes the categorization effect view a step further that by P1 latency the the human brain is not only capable of discriminating visual input of different categories of rather distinct shape, luminance, contrast and spatial frequency spectrum (e.g., verbal stimuli, faces and objects) but also sensitive to overall configural variations of stimuli under the same category (e.g., characters and pseudocharacters). This is consistent with the findings in VEP studies (e.g., Previc, 1988; Murav'eva, Deshkovich, & Shelepin, 2009; Schechter, Butler, Zemon, Revheim, Saperstein, Jalbrzikowski, & Javitt, 2005) and face perception ERP studies (e.g., Nakashima, Kaneko, Goto, Abe, Mitsudo, Ogata, & Tobimatsu, 2008; Pourtois, Dan, Grandjean, Sander, Vuilleumier, 2005) that P1 shows a low-pass spatial tuning function and its response depends on a visual pathway preferentially tuned to coarse-magnocellular inputs. In the current experiment, pseudocharacters elicited

greater P1 activities than characters and VMs. It is therefore proposed that the more familiar that coarse-scale configurational information of a particular stimulus is to the viewer, the easier it is to be extracted and more readily analyzed by the visual system.

Baseler & Sutter (1997) investigated the relationships between VEPs and M- and P-pathway sensitive manipulations including presentation eccentricity. They used a wide range of eccentricities including two comparable ones, 0.2 and 2.4 degrees, as used in the current study and found that the M-dominated component peak was small at the centre of the visual field and increased in amplitude outside the fovea. Together with the effect of eccentricity on the temporal properties of early ERP responses discussed above, this suggests that although stimulation received by the extrafoveal part of the retina may reach the visual cortex later, it excites neurons to a greater extent relative to that received by the fovea due to a high concentration of the low-spatial-frequency-sensitive rod cells in the extrafovea. However, the same pattern of eccentricity effect on P1 amplitude was obtained for all presentations with the exception of the contralateral P1 to LVF stimuli in the RH where the two eccentricities did not differ. Baseler & Sutter (1997) used a wider range of eccentricities including two comparable ones, 0.2deg and 2.4deg, as used in the current study. Therefore, it is reasonable to assume that it was the intrinsic nature of the stimuli rather than extrinsic presentation parameters that had caused the discrepancies between the two studies in the LVF. Baseler & Sutter (1997) undertook a VEP study which used monochrome patches as stimuli whereas the current experiment used verbal stimuli. Similar levels of P1 amplitudes for the LX and LF presentations in the RH suggests that when the RH receives and processes the coarse-scale information of extrafoveally presented character or character-like stimuli from the contralateral LVF, it is less efficient (relative to the LH to the RVF) in pooling the necessary resources as to produce greater P1 responses

than elicited by same stimuli in foveal presentations.

More direct evidence for this early hemisphere asymmetry in character recognition came from the VisField\*Hemisphere interaction observed in P1 amplitude comparisons. Previous VEP and ERP studies using English stimuli (e.g., Evans & Federmeier, 2009) have observed a general trend of increased P1 responses in the hemisphere ipsilateral to the stimulated visual field after information is transferred from the contralateral hemisphere. However, in the present study this pattern was found only for the LVF but not for the RVF stimulation. Although the P1 amplitudes tended to be lower in the LH than in the RH for RVF presentations, the LH responses were close enough to the RH responses to obviate a significant difference. Therefore, the following inferences can be drawn on the hemispheric asymmetry in Chinese character recognition: 1) the LH appears to be more specialized for processing general verbal stimuli, alphabetic or logographic; 2) this functional specificity of the LH may exert its effects on character reading as early as 60 ms post-stimulus onset; and 3) this functional specificity of the LH may render it the possibility of overcoming certain low-level perceptual effects on both the temporal and the strength properties of ERPs predicted by our visual anatomy.

#### 7.5.1.2 N1 and the topographic microstate of 160-200 ms

The early N1 started from ~ 140 ms over the occipito-parietal area contralateral to the stimulated visual field and then proceeded to the homologous area in the ipsilateral hemisphere before finishing at ~ 200 ms. The N1 has been identified by many researchers as a P-dominant component more tuned to processing of fine-scale information of visual inputs, as opposed to the M-dominant P1 (e.g., Murav'eva et al., 2009; Nakashima et al., 2008; Schechter et al., 2005; Previc, 1988).

Previous findings show that the P-pathway sensitive component systematically

decreased in latency and amplitude with increasing distance of the stimulus from the fovea (e.g., Baseler & Sutter, 1997; Harter, 1970). The reduced N1 responses to extrafoveal presentations compared to foveal presentations can be attributed to the structural difference of foveal and extrafoveal retina. As mentioned earlier, the fovea has the best visual acuity thanks to the densely packed cone cells within it which are highly sensitive to fine spatial patterns. Consequently, stimulation within the fovea excites greater neural responses in the N1 relative to extrafoveal stimulation. In the current study, significant N1 peak amplitude difference was observed only between characters in LX and LF presentations in the ipsilateral LH. Although there was a tendency of greater N1 peaks for RX stimuli than for RF stimuli, these numerical differences did not reach statistical significance; in contrast, LF-presented pseudocharacters and VMs showed no sign of eliciting larger N1 peaks compared to LX-presented counterparts. This suggests that as the contralateral hemisphere where the majority of stimuli's fine features were first analyzed, the RH may be less sensitive to eccentricity variations in the LVF as the LH to those in the RVF, in particular for non-lexical stimuli such as pseudocharacters and VMs.

In the respect of latency differences, the group-averaged ERP waveforms showed a strong tendency of delayed N1 peaks for RF presentations relative to those for RX presentations in the RH. From a more global view, this pattern of difference reached significance in TFMaxGFP data. It is not clear from the literature why the eccentricity differences in the ERP latency of previous stages, which gradually faded out by the end of the ipsilateral P1 in the current study, should reappear in the N1 yet in the opposite pattern. Neither the visual anatomy of human retina nor the neural responsibilities of the P-dominant N1 favors extrafoveal inputs as to elicit earlier responses relative to foveal inputs at this stage. Apart from showing the opposite

direction, the effect of eccentricity on latency in the N1 also differed from that observed in the C1 when stimulation initially reached the primary visual cortex in terms of their sustainability. In contrast to the more transient effect originated in the C1, eccentricity-related latency differences that emerged in the N1 saw a consistent continuation through the following ERPs till the end of the 500-ms epoch. It is proposed that the eccentricity modulations in the temporal property of the ipsilateral N1 reflected the outcome of perceptual processing of inputs so far. Specifically, the P-dominant N1 is mainly responsible for the processing of fine-scale information in stimuli and this process starts in the hemisphere contralateral to the stimulated visual field. The fovea has more numerous and more active cone cells and therefore can extract fine features of inputs better than the extrafovea. This may lead to the contralateral N1 extracting more low spatial frequency information from foveal stimuli and analyzing them to a greater extent compared to extrafoveal stimuli. As this more packed information flow progresses towards the ipsilateral hemisphere, the ipsilateral N1 latency may be delayed for foveal stimuli. In the context of the current experiment which used characters and character-like constructs as stimuli, the fact that the TFM<sub>MaxGFP</sub> of ipsilateral N1 was delayed only for RF presentations relative to RX presentations shows that the fine-scale information of LF stimuli first gathered in the RH was not sufficient enough to significantly delay the timing when it reached the ipsilateral hemisphere. The two main effects of eccentricity and stimulus type obtained in another temporal measure of the ipsilateral N1 map provides further support for the hypotheses that the N1 is when crucial feature-level evidence is accumulated before attempting lexical retrieval and that foveal inputs are favorably processed in this stage. Specifically, the topographic pattern of ipsilateral N1 lasted longer for foveal presentations versus extrafoveal presentations and for characters/pseudocharacters versus VMs.

In agreement with the 'P-sensitive processing' view of the N1, studies in word and face recognition have most commonly reported the earliest ERP amplitude differences between words/faces and stimuli of other categories in the N1 and attributed this difference to certain feature-level familiarity effect. In the current study, larger N1 peak amplitudes were found for characters than for VMs. Notably, this greater sensitivity to characters was also manifested in global topographic strength. It is argued that after the coarse-scale processing in the previous stages, the N1 activations mainly involve analyzing stimulus features at finer levels such as strokes, stroke clusters and spatial interactions between radicals. VM stimuli were constructed with stroke fragments and contained no orthographic information that the N1 is specially sensitive to. Naturally, N1 responses to VMs were significantly weaker than those to characters.

There was also evidence for hemispheric lateralization in the LH in terms of N1 amplitude and more importantly, this left-lateralization was observed for RVF presentations only. Furthermore, it was in the LH that the N1 peak amplitude showed a numerical difference between characters and pseudocharacters presented in the LF location. It was in the LH that we found the only ERP difference between characters and pseudocharacters (LF\_Ch vs LF\_Ps) at the N1 stage due to significantly reduced N1 responses under the LF\_Ps (and also LF\_VM) condition compared to the LF\_Ch condition. It can be concluded from the above discussion regarding the eccentricity effect in the N1 that this discrepancy does not reflect genuine lexical activation. Instead, it was more due to difference between the two hemispheres in their ability of processing sub-lexical information. More specifically, when pseudocharacters were presented in the RVF, the fine-scale information such as strokes and stroke clusters were first processed by the N1 activation in the LH which is highly tuned to analyzing these regular orthographic features. Therefore, the stroke and radical information in RVF\_Ps

stimuli could be efficiently utilized by the LH as to elicit similar level of N1 responses as RVF\_Ch stimuli. In addition, the similar level of N1 responses for RVF-presented characters and pseudocharacters presented in the contralateral LH was retained in the ipsilateral RH though amplitudes considerably reduced. In contrast, LVF presentations activated N1 responses firstly in the RH where the orthographic features were not utilized as efficiently as in the LH. The trend of stronger N1 activations in the LH in response to LF\_Ch stimuli compared to LF\_Ps stimuli may be a combined result of better visual acuity in the LF location compared to the LX location and the LH's sensitivity to linguistic stimuli so that no such character-pseudocharacter difference in the LX location or in the RH.

#### 7.5.1.3 P2 and the topographic microstate of 200-250 ms

As mentioned in the introduction to this Chapter, the positive deflection of ERP between 200-250 ms has received less attention in the literature compared to other components within the first 500 ms after stimulus presentation. Indeed, the posterior P3 has more often been discussed as the next ERP component after the N1 in studies investigating word recognition.

In the current study, the P2 was observed along the midline centro-frontal area with mean peak latency of around 220 ms. Similar to the proceeding stage of the N1, the P2 peaks were also more activated for character presentations than for VM presentations. However, in contrast to the N1 where significant difference between characters and pseudocharacters (at the LF location) was obtained in the LH with enhanced brain activations for characters, the P2 amplitudes differentiated between characters and pseudocharacters in a reversed pattern in the RH when they were presented in the RVF.

Although no ERP studies have specifically compared how the brain responds to

characters and pseudocharacters in the centrofrontal P2, some fMRI studies obtained similar activation patterns in the frontal regions where the P2 is associated with activation of phonological information. For example, Lee, Huang, Kuo, Tsai, & Tzeng (2010) found greater brain activations were involved in the frontal regions including BA9 when participants silently naming pseudocharacters compared to characters. The authors attributed this effect to different phonological mechanisms for reading these two stimulus types, i.e., greater activations for assembled grapheme-to-phoneme phonology vs directly accessed phonology. However, it is unlikely that the P2 amplitude differences between characters and pseudocharacters in the current experiment resulted from phonological processing, mainly due to the following three reasons. Firstly, unlike the naming task or other phonologically-related tasks, the Reicher-Wheeler task used in the current experiment does not require participants to process stimuli's sound. Secondly, well-defined P2 peaks were also identified for VM stimuli which contained no phonological information. Thirdly, it is one of the most robust findings in word recognition literature that phonological processing mainly takes place in the LH. However, it was in the RH that RVF\_Ps stimuli elicited higher P2 amplitudes than RVF\_Ch stimuli. It therefore makes little sense why the less phonology-sensitive RH, rather than the LH, was adept enough to capture the differences in the way the sound of characters and pseudocharacters were attempted, if there was such processes.

There is also evidence in the literature associating the P2 with lexical retrieval. For example, in a study using native English speakers learning Chinese as a second language as participants, Liu et al. (2006) compared their ERPs to English words and Chinese characters at different times of their Chinese course. They observed larger amplitudes for Chinese characters in the occipital N200 (N1) and the centro-frontal P200 (P2) in their first recording. In their second recording one term later, the

difference between the two languages in the N200 amplitude was eliminated while the language difference in the P200 amplitude was unaffected by learning experience. The authors therefore concluded that the N200 and the P200 reflect distinct functional processes. Larger amplitudes for Chinese characters in the N200/P200 in the first recording indicated more visual processing (occipital N200) and lexical access (centro-frontal P200) efforts were needed for processing Chinese. In the second recording, the P200 amplitude remaining larger for Chinese stimuli indicated that reading Chinese was still a demanding task at the lexical access level, while the disappearance of N200 differences suggested that the visual analysis had been quickly accommodated. A more general opinion along the similar line is that the P2 may be part of some cognitive matching system that compares perceptual inputs with mental representations either stored in memory or built from a linguistic context (Curran & Dien, 2003; Evans & Federmeier, 2007; Federmeier, Mai, & Kutas, 2005; Luck & Hillyard, 1994; Misra & Holcombe, 2003, etc.).

Findings in the current experiment seem to support the lexical retrieval and the perceptual matching views of the P2. Specifically, although the VM stimuli also elicited rather visible P2 peaks, the P2 microstate topography in response to VMs exhibited earlier offset relative to characters and pseudocharacters. This may suggest that the brain was unable to retrieve any entries in the mental lexicon based on the VM inputs, which resulted in an early termination of the searching and matching processes. In contrast, pseudocharacters contained two valid radicals for which matching entries could be accessed in verbal memory and therefore had longer-lasting P2 map compared to the VMs with greater local (over the frontal sites) and global strength. In addition, various studies in the literature have shown that the two hemispheres encode verbal stimuli in distinct ways with the RH more sensitive to visuospatial features, such as

letter case, word length, while the LH stores verbal information at a more abstract level (Berrini, Capitani, Della Sala, & Spinnler, 1984; Berrini, Della Sala, Spinnler, Sterzi, & Vallar, 1982; Dee & Fontenot, 1973; Goldberg, Perfetti, Fiez, & Schneider, 2007; Kimura, 1966). If the P2 did reflect perceptual matching processes involved in retrieving relevant entries in the stored memory, such processes would be expected to be stronger in the RH especially for stimuli containing novel or unfamiliar visuospatial features as in pseudocharacters. Therefore, the present study's observation of higher P2 amplitude in the RH for pseudocharacters in the RVF relative to characters presented in the same visual field (along with a numeric trend of such Ps-Ch difference in the LVF) may imply that abstract representations of the two component radicals in a pseudocharacter were activated in the LH in a similar manner as those in a character while discarding the unfamiliar inter-radical relationship which, however, the RH was more sensitive to capture and further process as to elicit greater neural excitations.

The sLORETA results showed that the BA9 area in the right hemisphere, including the right medial frontal gyrus and the right superior frontal gyrus, was involved in producing surface stimulus differences during the POI of 200-250 ms. This is consistent with previous fMRI findings that activations in these areas were related to memory processes and were increased as the retention or manipulation of the visuospatial features of a stimulus became more demanding (Manoach, Schlaug, Siewert, Darby, Bly, Benfield, Edelman, & Warach, 1997; McCarthy, Puce, Constable, Krystal, Gore, & Goldman-Rakic, 1996; Cohen, Perlstein, Braver, Nystrom, Noll, Jonides, & Smith, 1997, etc.). In particular, Tan, Liu, Perfetti, Spinks, Fox, & Gao (2001) used Chinese characters as stimuli and their data suggests that activations in the middle frontal gyrus may reflect the cognitive processes of coordinating and integrating the intensive visuospatial analysis demanded by logographs' square configuration and

the semantic (or phonological) analysis when required by the experimental task.

#### 7.5.1.3 P3 and the topographic microstate of 300-335 ms

The P3 peak, maximal on parietal sites, appeared at around 300 ms post stimulus onset for extrafoveal presentations and approximately 30 ms later for foveal presentations in the present study. Unlike the earlier P1, N1 and P2 which all showed good peaks in response to presentations at both eccentricities (in spite of modulatory effects on peak amplitude and latency), the P3 response to foveal presentations took the form of a more flattened out slow wave with hardly any visible peaks, especially for the RF presentation. This can be attributed to two factors. Firstly, it is well-acknowledged that the P3 is highly task-dependent. It appears more prominent in tasks that explicitly or implicitly demand subjects' reaction towards certain properties of a stimulus on its own or as compared to the task or other stimuli. In the area of word recognition, such stimulus properties may include its lexical status (as in the lexical decision task, e.g., Schacht & Sommer, 2009), its orthography (as in the orthographic judgement task, e.g., Liu et al., 2003), its phonology (as in the phonological judgment task, e.g., Bentin et al., 1999) and its semantics (as in the semantic categorization or judgement task, e.g., Zhang et al., 2009). In contrast, the Reicher-Wheeler task is a passive viewing task which, comparable to everyday reading conditions encourages subjects to focus on the visual identity of words rather than to pay special attention to the non-visuoperceptual properties. Secondly, a substantial bulk of studies in the literature have shown that the P3 peak is affected by several lines of cognitive factors including difficulty, confidence and uncertainty, showing larger amplitude when subjects feel a task or stimulus more difficult and (accordingly) less certain or confident (see Picton 1992's review). In the present study, therefore, for relatively easier stimuli with which subjects felt more confident, as presented from within the fovea in a passive-viewing task, the P3 appeared

as a deflection-absent current flow with mean amplitude of around 2  $\mu\text{V}$  or below except for the LF presentations in the RH<sup>7</sup>. In addition to strength modulations, the temporal characteristics of the P3 were also affected by presentation eccentricity. It is not unusual for researchers to propose that the P3 latency indexes stimulus evaluation time and to interpret delayed P3 latency observed for certain stimulus types (e.g. Andreassi & Juszcak, 1984) or in certain clinical groups (e.g., Bruder, Towey, Stewart, Friedman, Tenke, & Quitkin, 1991) as reflecting increased difficulty of evaluation. However, this line of argument does not seem to apply to the findings in the present study. It is unlikely that the delayed P3 latency for foveal presentations was because they were more difficult to process than their extrafoveal counterparts. Using a comparable experimental procedure, Leuthold & Sommer (1998) found that eccentricity affected the peak latency in two ERPs, the P265 and the P300 with the former appearing at a later latency for extrafoveal presentations while the latter showing the reversed pattern. They argued that the increase of P265 latency with retinal eccentricity indicates an effect on an early sensory preprocessing stage and the reversed eccentricity effect in P300 latency suggests an influence on a stage where perceptual evidence is accumulated. Findings in the present study lend support to the argument that P3 latency is sensitive to the duration of perceptual processing, that is, accumulation of more perceptual evidence for foveally presented stimuli may result in its delayed P3 latency compared to those presented outside the fovea. On the other hand, findings of the present study clearly show that P3 was not a stage of perceptual processing per se and such an eccentricity effect due to perceptual processing had taken place before 300 ms (refer back to panel A of Figure 7.12 for temporal effects of eccentricity in IpsiN1 and P2). The fact that eccentricity effect on ERP latency reappeared in the IpsiN1 after it was eliminated by

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<sup>7</sup> An extensive search in the literature found three ERP studies that used the Reicher-Wheeler task, i.e., Coch & Mitra (2010), Martin, Nazir, Thierry, Paulignan, & Démonet (2006), and Martin et al., (2007), none of which mentioned the P3 component.

the end of IpsiP1 further suggests that such perceptual analyzing and evidence accumulating processes started soon after visual inputs reached the primary visual cortex (see discussion for C1, P1 and the topographic microstate of 60-100 ms for details). Since Leuthold & Sommer was a rather comparable study to the present one in terms of stimulus size ( $\sim 0.3\text{deg}$  vs  $\sim 0.5\text{deg}$ ), presentation eccentricities (0.15/1.2deg vs 0.15/2.0deg), and task (two-choice task), the discrepancy in the timing when such eccentricity effect was initially observed between the two studies can only be explained by the nature of stimuli. Leuthold & Sommer used low-level visual stimuli (square, diamond, circle, octagon) while the present study used verbal stimuli (characters, pseudocharacters and VMs to characters).

The temporal and strength characteristics of the P3 were also affected by stimulus type. Although no significant stimulus effect was found in P3 peak latency, results of topographic pattern analysis during the POI of 300-335 ms show that the onset and offset of P3 microstate topography in response to characters were delayed relative to VMs, as a consequence of the delayed microstate offset and prolonged microstate duration for characters in the preceding stages (refer back to panel A of Figure 7.12 for temporal effects of stimulus type in IpsiN1 and P2). In terms of P3 strength, an interaction between hemisphere and stimulus (PO3\_PO4) revealed augmented P3 peak amplitude for pseudocharacters compared to characters in the RH; and an interaction between visual field and stimulus in the MaxGFP of P3 microstate further specified this character-pseudocharacter difference to the LVF only. These findings resonate with the observations in Martin, Kaine, & Kirby (2006) that P3 amplitude in normal subjects was larger for pseudowords than for words in the RH<sup>8</sup>. As discussed earlier, the character-pseudocharacter differences identified in the preceding

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<sup>8</sup> Note that they were labelled as 'nonwords' in Martin et al., (2006) despite being pronounceable letter strings.

stages can all be attributed to the less efficient processing of pseudocharacters when they were presented in the LVF compared to when presented in the RVF. Alongside the observation of higher P3 peak amplitude in the RH than in the LH for stimuli presented in the LVF only (as well illustrated in its corresponding microstate topographic maps, see Figure 7.13), the character-pseudocharacter defiance observed here in the P3 strength also suggests that when the brain responds to the outcome of early visuoperceptual analysis of stimuli (C1, P1 and N1) and mental representation retrieval (P2) at around 300 ms, the RH showed greater uncertainty to the perceptual evidence accumulated from stimuli presented in the LVF and the cognitive identification assigned to them compared to the LH; furthermore, this increase of uncertainty was significantly stronger for pseudocharacters relative to characters.

#### 7.5.1.4 N400 and the topographic microstate of 450-500 ms

At around 450 ms post stimulus onset, a negativity of the ERP waveforms appeared over the occipito-temporal area in response to characters and pseudocharacters. Due to the present experimental procedure epoching of ERP waveforms had to take an upper cutoff at 500 ms before this negativity developed into its maturity. Although the N400 modulations could not be examined at the local peak level, topographic pattern analysis during the POI of 450-500 ms (corresponding to the 'primitive' N400) yielded informative results at the global level.

Notably, the N400 microstate topography, unlike all preceding stages, was no longer affected by visual field. Not only one and the same topographic map was identified for each stimulus type regardless of visual field (and eccentricity), the onset and MaxGFP/MeanGFP of these maps were also free of visual field effects<sup>9</sup>. In addition, a negativity over the occipito-temporal area was found only for characters and

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<sup>9</sup> Analysis of the TFMaxGFP, offset, and overall duration of these maps were not applicable here.

pseudocharacters whereas the topographic configuration in response to VMs exhibited a bilateral positivity during this POI over the same scalp area (refer back to Figure 7.13). This is consistent with observations in previous studies that words elicit a larger N400 than nonwords (e.g., Bentin, 1987; Bentin et al., 1985; Coch & Mitra, 2010; Rugg, 1987). Apart from the word-nonword effect in the N400, there is substantial evidence of a word-pseudoword effect with words eliciting smaller N400 compared to pseudowords (e.g., Bentin et al., 1999; Coch & Mitra, 2010; Hauk, Davis, Ford, Pulvermüller, & Marslen-Wilson, 2006a; Hauk et al., 2006b; Holcomb & Neville, 1990; Pulvermüller, Mohr, & Lutzenberger, 2004). Similar pattern of character-pseudocharacter difference in the N400 has also been reported (e.g., Wang et al., 2010). There are currently two major views on what kind of psychological processing is reflected in the N400 effects. The 'integration' view proposes that the N400 reflects a post-lexical stage during which the semantic information of a critical word is integrated with the working context, e.g., meaning of the whole sentence as in the case of sentence reading or information of the same word in other aspects such as phonological and orthographical as in the case of single word viewing. Alternatively, the 'lexical' view argues that the N400 indexes lexical activation of a word which can be facilitated by the supporting context, e.g., the sentence or discourse it's embedded in or other properties of the word (see Lau et al., 2008 for review). Based on these two accounts, the observation of a greater N400 response to pseudowords has typically been interpreted as reflecting enhanced difficulty of, or more efforts needed for, the integral or lexical process relative to words.

In the present study, the N400 tended to exhibit stronger global strength in response to characters than to pseudocharacters, which may seem contradictory to previous research. However, a close comparison between the present study and those cited above revealed that this seemingly 'external' inconsistency is paralleled by an

`internal' consistency in that the direction of word-pseudoword or character-pseudocharacter effect in the N400 appears to be correlated with that in the N1. Specifically, the present study found greater N1 response to characters than to pseudocharacters whereas the above-cited studies all reported the opposite effect in the N1 except Wang et al. (2010) which did not mention a N1 activation<sup>1011</sup>. Therefore, it can be hypothesized that when two verbal stimulus types both elicit the N400, the one which is favourably processed in the N1 stage (words/characters) will show the same superiority effect over the other one (pseudowords/pseudocharacters). More interestingly, Pulvermüller et al., (2004) described a reversed word-pseudoword effect within the time window of 160-320 ms in healthy subjects with words eliciting more positive ERPs than pseudowords; in contrast, patient subjects showed the opposite pattern with smaller positivity for words compared to pseudowords. The positive ERPs in the present study (P1, P2 and P3) all showed greater response to pseudocharacters relative to characters and the negative ERPs (N1 and N400) were more activated for characters than for pseudocharacters. Taken together, these findings suggest that, there might exist certain negative correlation between the positive and negative ERPs in terms of their strength modulation pattern (as far as words/characters and pseudowords/pseudocharacters are concerned).

In the respect of hemispheric lateralization, the N400 topography to characters showed a rightward-skewed activation, which is consistent with previous findings in the literature (see Van Petten & Luka, 2006 for a review). Despite this scalp distribution, many studies located a LH generator responsible for the N400 using split-brain patients,

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<sup>10</sup> It should be pointed out that the character-pseudocharacter effect in the N1 in the present study interacted with visual field and eccentricity due to lateralized display.

<sup>11</sup> Wang et al. did not report any negative wave during the typical N1 time window over the posterior sites; instead, an anterior N120 was described with no effect of stimulus type. The posterior negativity in the other cited studies all peaked at around 200 ms except in Hauk et al., (2006a) (160 ms) and have accordingly been labelled as the N200 and the N160.

intracranial recording or MEG and therefore argued that the rightward skew of N400's scalp topography is a case of 'paradoxical lateralization' due to fissural morphology and conductance properties (for review of N400 and paradoxical lateralization, see Curran, Tucker, Kutas, & Posner, 1993 and Lau et al., 2008; for more general discussion of paradoxical lateralization, see e.g., Brigell, Rubboli, & Celesia, 1993 and Tomberg, Weinberg, Vrba, & Tcheung, 2005).

## 7.5.2 A macro-developmental approach to individual research issues

### 7.5.2.1 The character superiority effect in lateralized display

As the character superiority effect (along with other context effects in radical perception) was found in central visual field in the previous chapter, the initial motivation of the present study was to assess whether the character superiority effect exists in lateralized presentation and whether it is differentially affected by the two hemifields. The behavioral results showed that characters were identified more accurately than pseudocharacters and VMs in either visual field and the size of this superiority was symmetrical in either visual field, too. These findings are consistent with previous studies which also reported 'balanced' behavioral responses to characters presented in the two visual fields (e.g., Fang, 1997; Rastatter et al., 1989; Tang et al., 1988; refer back to Section 7.2.1 for details). These findings have two major implications.

First, the character superiority obtained in the present study indicates that the benefits of familiar coarse-scale configurational information are also available to laterally presented characters as to produce better identification performance. Although the behavioral results showed the character superiority in response accuracy and time over pseudocharacters irrespective of visual field and eccentricity, the ERP differences between characters and pseudocharacters were all modulated by the latter two factors

except in the final stage of the (primitive) N400 near the end of the 500 ms epoch. The local and global ERP differences between the three stimulus types during the POI of 60-100 ms are believed to be the neural correlates of such coarse-scale perceptual facilitation. Specifically, a main effect of stimulus type showed that pseudocharacters elicited greater responses locally at the P7\_P8 and PO7\_PO8 sites and globally for the GFP of the microstate map during the POI of 60-100 ms. An additional three-way interaction at the P7\_P8 further specified that these differential P1 responses occurred only when stimuli were presented within the fovea in the RVF. As discussed in the proceeding section, given this very early latency which has been associated with M-sensitive coarse-scale processing in many other studies and the similarity in the overall outline and the inter-radical spatial relationships between characters and their matched VM items, it is hypothesized that the overall outline and the inter-radical relationships in pseudocharacters were novel to participants and therefore were not as readily extracted by the visual system as characters and VMs during this stage. It is also worth mentioning that the VMs also shared the same overall amount of pixels as characters and that could have resulted in similar levels of P1 amplitude between characters and VMs, as compared against pseudocharacters. However, this possibility is less likely. Gong, Lv, Liu, Zhang, & Miao (2008) examined whether identical stimuli (three circles, two above the other one, enclosed in an oval shape) were processed the same way when participants were induced to perceive it either as a schematic face or English letters 'O'. Their results showed that although the stimuli were identical in the two different priming contexts, they elicited greater ERP responses around 40-100 ms when participants were lead to perceive them as upper-case 'O's than when participants perceived them as representing schematic faces. This suggested that it was the spatial configurational information of a target stimulus that the visual system was focusing at

this initial stage. The ERP differences between characters and pseudocharacters at later stages will be discussed below in the following sections.

Second, the absence of any visual field difference in behavioral identification response to characters suggests that the two hemispheres are overall equally efficient and equally involved in character processing. Since the behavioral responses in the present study reflect the outcome of a series of individual processes, from the initial perceptual analyzing to the motor programming later on, within a second after stimulus presentation (mean RT for characters across four screen locations was  $\sim 1050$  ms), there are two possibilities of this 'overall equal efficiency'. One possibility is simply that the two hemispheres are balanced throughout each stage of character processing so that it makes no difference whether the LH or the RH receives a character input initially; the other possibility is that the initial-receiving hemisphere does affect how a character stimulus is analyzed at early stages, however, such early influences have little impact on behavioral responses after one second from character onset. In either case, the implication is that, compared to the generally observed left lateralization in English word recognition, the RH seems to be more involved in some or all stages of Chinese character processing. Another interesting point to emerge from the behavioral results is that, although the discrimination accuracy for pseudocharacters showed a flat pattern across the four screen locations, the RT to pseudocharacters was affected by an interaction between presentation eccentricity and visual field with the extrafoveally presented pseudocharacters in the RVF were responded to more quickly than those in the LVF. Like the hemispheric asymmetry pattern often observed in English word recognition, this suggests that the RH was overall less efficient in processing pseudocharacters than the LH which led to greater uncertainty about their identities and thus longer RTs. The ERP evidence for hemispheric asymmetries in character and

pseudocharacter recognition will be discussed below.

In summary, it can be concluded from the behavioral results that the benefits of familiar coarse-scale configurational information are also available to characters presented away from the central fovea and that different extent of involvement of the RH may be responsible for the different lateralization patterns between Chinese characters versus English words and pseudocharacters. The ERP evidence for this conclusion is discussed below.

#### 7.5.2.2 Hemispheric asymmetries in Chinese character recognition

The behavioral results of the present study revealed no visual field effect in character identification accuracy or response time which suggests an 'overall equal involvement' between the two hemispheres. In contrast, a RVF advantage was observed for pseudocharacters presented outside of the fovea in terms of RT, which strongly suggests a left-lateralized neural network in processing this type of stimuli. The ERP results provided clearer answers to questions such as if the absence of any behavioral visual field effect for characters was indeed due to symmetrical hemispheric activation throughout each stage of character processing or instead reflected a zero impact of hemispheric asymmetries on character identification accuracy or RT after one second from character onset. The ERP results also provided more direct evidence for the LH dominance in pseudocharacter processing. Indeed, although the behavioral results showed that character identification performance and the size of character superiority over pseudocharacters, as the ultimate outcome, were not affected by visual field or eccentricity, the ERP responses to characters and the ERP differences between characters versus pseudocharacters were almost all modulated by the two factors except in the final stage of the (primitive) N400 at the end of the 500 ms epoch.

The earliest ERP evidence for hemispheric asymmetries in character recognition

emerged during the POI of 60-100 ms when a distinct microstate topography was obtained for stimuli presented in each of the four screen locations except for characters presented in the RVF. Specifically, the microstate maps during this POI demonstrated that cortical responses to foveal stimuli had fully developed into the contralateral P1 (in the LH for RF stimuli and in the RH for the LF stimuli) while the topographic maps for LX stimuli were still in the C1 stage, which accordingly resulted in the difference in P1 peak latency between foveal and extrafoveal stimuli in the LVF. In contrast, in the RVF, unlike RX\_Ps and RX\_VM stimuli which elicited a topography featuring concurrence of remaining C1 in the ipsilateral hemisphere and starting of early P1 in the contralateral hemisphere, RX\_Ch stimuli during this period exhibited a topographic configuration synchronized with their foveal counterparts, namely, mature contralateral P1 activation in a broader occipito-temporal area reaching towards the ipsilateral hemisphere (refer back to Figure 7.8). These findings show an interaction between bottom-up visual-anatomical constraints and top-down stimulus-specific influences in the temporal domain of ERP responses to characters and character-like stimuli as early as 60 ms. As discussed earlier, fovea input sampled with more cone cells reached the primary visual cortex more quickly than extrafovea input. However, this bottom-up effect of eccentricity can be modulated by the higher-order characteristics of stimuli so that the visual pathway in the LH may be language-sensitive enough to speed up the relay of extrafoveal character stimulation at 2deg in the RVF from retina to the visual cortex as to 'catch up with' that of foveal character stimulation at 0.15deg in the same visual field (refer back to the 60-100 microstate part in Section 7.5.1 for detailed discussion). This speculation is supported by the LORETA results that source generators were identified as responsible for the ERP differences during this POI between RX\_Ch vs RX\_Ps and RX\_VM in the BA 18 and 19 areas in the LH,

respectively.

In addition, visual field also showed modulatory effect on the local peak strength of the P1. Specifically, the general trend of increased P1 responses in the hemisphere ipsilateral to the stimulated visual field after information is transferred from the contralateral hemisphere was observed only for the LVF but not the RVF stimulation. This indicates that the LH was particularly sensitive to characters and character-like stimuli and that more information got extracted and processed in the LH when it received these types of input from the RVF than what the RH was able to process when it received input from the LVF. Further evidence of hemispheric asymmetry during the early stage of visual processing was reflected in the character-pseudocharacter difference when they were presented in the RVF within the fovea with lower P1 amplitude for RF\_Ch than for RF-Ps stimuli. As discussed above and back in Section 7.5.1.1, stronger P1 in response to pseudocharacters than to characters and VMs at this stage may be explained by the fact that the coarse-scale configurational information in characters and VMs was familiar to the visual system and accordingly required a relatively low threshold for the neurons to fire; in contrast, the coarse-scale configurational information in pseudocharacters was novel to the visual system and thus less readily extracted, resulting in a higher firing threshold. The fact that this distinction was observed only in the RF location suggests that only when stimuli were presented within the fovea where better visual acuity was available and when the LH was the initial-receiving hemisphere that the coarse-scale configurational information in pseudocharacters could be perceived as different from that in characters and VMs.

To sum up the above, the ERP evidence in the present study shows that visual field affects the initial stage (including the C1 and the P1) of character processing with the LH appearing more specialized and efficient than the RH in extracting the coarse-

scale configurational information in characters. As noted in the Introduction to this chapter, very few ERP studies reported pre-N1 hemispheric asymmetries in word or character recognition. This seems to be in contradiction with the common assumption that the RVF advantage in word recognition is due to the fact that words presented in the RVF initially project to the LH rather than the RH, which implies that the two hemispheres are not equally efficient in the initial stage of word processing and this initial asymmetry has a significant effect on how the brain responds to words stimulated from either visual field in later stages and ultimately the behavioral response. It is proposed that the following factors may be responsible for the absence of early hemispheric asymmetries in most studies of word or character recognition. Firstly, as noted by Barber & Kutas (2007) and Hauk et al. (2006a, 2006b), given their relative weakness in strength and transiency in duration, early effects are more vulnerable to variability across items and subjects and therefore more difficult to detect. The low detectability of early effects was further complicated by methodological limitations in the existing literature. Indeed, the electric neuroimaging procedure<sup>12</sup> performed in the present study is a most recent development of ERP data analyzing method that has not, to my knowledge, been applied in any published work investigating hemispheric asymmetries in word or character recognition. As a consequence, all relevant studies cited above were not able to examine whether the two hemispheres respond differentially to laterally presented words right from stimulus onset. Even when there did exist very early hemispheric asymmetries in word or character processing, for example in the response latency for stimulation from their contralateral visual field, these early differences may have lost their trace by the time window (P1) when ERP

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<sup>12</sup> The term of 'electrical neuroimaging' was first proposed by Murray and colleagues in 2004. It is a four-step procedure of ERP data analysis on the global topographic level, in contrast to the local peak analysis. See Section 7.3.7 for details.

analysis started in previous word or character recognition studies. Secondly, unlike behavioral studies which have to rely on hemifield presentation to examine hemispheric differences, ERP studies in the existing literature have mostly used central presentation, which allows for the interference from either hemisphere. Last but not the least, almost all previous ERP studies investigating hemispheric asymmetries in word or character recognition used a stimulus exposure duration of more than 100 ms. Considering that the present study obtained evidence of pre-N1 hemispheric asymmetries with stimuli presented for 17 ms, it is possible that such brief presentation pushed the visual system to its limit so that the advantages of one hemisphere over the other were revealed in terms of the speed of input intake and the ease of initial analysis whereas longer presentation durations may allow the less efficient hemisphere to extract sufficient amount of information from the input as to show similar level of response as the more efficient hemisphere.

Compared to studies which did report pre-N1 hemispheric asymmetries, the finding of LH advantage is consistent with the findings in studies using English words (e.g., Cohen, et al., 2000). Hsiao et al. (2007) was the only ERP study, to my knowledge, that reported hemispheric asymmetries in the P1 response to Chinese characters. They observed higher P1 amplitude in the RH than in the LH, which superficially contradicts the finding of the present study. Hsiao et al. argued that this opposite pattern in contrast to the findings in English studies can be explained by the greater visual complexity of Chinese characters which demands more elaborated visuo-spatial analyses. On these grounds, it resonates the view of the present study that the RH plays a more important role in the recognition of Chinese characters than in that of English words. The relative importance of the RH in character identification has been indicated by the absence of any behavioral effect of visual field, in contrast to the robust RVF advantage in word

recognition, and will be further discussed in the POI of 200-250 ms.

The LH advantage as the initial-receiving hemisphere over the RH continued to influence how the fine features of stimuli were analyzed in the two hemispheres in the N1 (140-200 ms) of the present study. Specifically, the N1 response was significantly left-lateralized when stimuli were presented in the RVF; pseudocharacters presented in the RF location elicited similar level of N1 response in the LH as characters presented in the same location whereas pseudocharacters presented in the LF location elicited significantly weaker N1 response than characters in the same location; and the only significant eccentricity difference in the N1 peak amplitude was found in the LH between LX\_Ch and LF\_Ch stimuli, in contrast to the fact that in the same hemisphere RX\_Ch stimuli elicited similar level of N1 activation as RF\_Ch stimuli and that the RH did not appear significantly more responsive to foveally presented characters than their extrafoveal counterparts regardless of visual field. Although no ERP studies using central or lateral presentation reported hemispheric asymmetries in the N1 response to Chinese characters, there exists such fMRI evidence. For example, Liu et al. (2008) used characters, pseudocharacters and artificial characters (re-arranged strokes) and observed greater activation in the left middle fusiform gyrus during real and pseudo character processing compared to artificial characters.

In the following time window of P2 (POI of 200-250 ms), there was no significant hemispheric asymmetry observed for characters despite a numeric trend of higher P2 amplitude in the RH than in the LH. In contrast, the P2 amplitude was greater in the RH for pseudocharacters presented in the RVF than in the LH. Recall the discussion above that neural activations during this POI in the centro-frontal area reflected the process of lexical retrieval. Absence of any hemispheric difference for characters may suggest that the two hemispheres were equally efficient in retrieving

their corresponding stored entries, in contrast to a more lateralized network for pseudocharacters showing heavier matching and retrieving workload in the RH due to the unfamiliar inter-radical visuo-spatial features in pseudocharacters. Moreover, the RH was more 'alerted' to such novel features and thus 'called for' more processing resources especially when pseudocharacters had been initially presented in the RVF and undergone more specialized analysis at coarse and fine-tuned scales in previous stages (see earlier discussion of visual field related effects in the P1 latency, P1 amplitude and the N1 amplitude for details).

As discussed earlier, findings in the present study support the argument that the P3 reflects the brain's response to the outcome of stimulus evaluation and other internal decision-making processes. Naturally, how efficient the brain processed stimuli of a certain type in the previous stages had an impact on how confident it was towards the result of visual and cognitive analysis for that type of stimuli so far. From a global view, the microstate topography during the POI of 300-335 ms showed stronger MaxGFP in response to pseudocharacters than to characters when they were presented in the LVF; at the local peak strength level, the P3 peak amplitude recorded on sites PO3\_PO4 was augmented for pseudocharacters compared to characters in the RH. Given that the character-pseudocharacter differences identified in the preceding stages can all be attributed to the less efficient processing of pseudocharacters when they were presented in the LVF compared to when presented in the RVF, the character-pseudocharacter differences observed here in the P3 strength may also have the following indication. That is, when the brain responds to the outcome of early visuoperceptual analysis of stimuli (C1, P1 and N1) and mental representation retrieval (P2) at around 300 ms, the RH showed greater uncertainty and less confidence (as to whatever perceptual evidence accumulated from and whatever cognitive identity assigned to stimuli) than the LH

when they were presented in the LVF. Besides, this increase of uncertainty was significantly stronger for pseudocharacters compared to characters.

As for the N400, due to the 500-ms cutoff point of the EEG segments used in the present study, direct comparisons between the two hemispheres in terms of local peak latency and amplitude were not possible. Results of the topographic pattern analysis did show a left-lateralized microstate topography in response to pseudocharacters whereas the two hemispheres appeared more balanced on the topographic map in response to characters (refer back to Figure 7.15), which is consistent with the behavioral results that pseudocharacters presented in the RVF were identified with shorter RT relative to those presented in the LVF. However, since the POI of 450-500 ms only reflected the pre-mature state of the N400, a precise assessment of whether the two hemispheres respond differently to characters and pseudocharacters presented in either visual field at the N400 peak latency is still needed.

To sum up the above, differences between the two hemispheres in character recognition as initial-receiving hemisphere occurred as early as 60 ms post stimulus onset with the RVF/LH showing an advantage over the LVF/RH in terms of data transfer speed for extrafoveally presented characters. After this initial stage, the advantage of the RVF/LH was also observed in the processing of character-like stimuli (pseudocharacters and VMs) in the P1 and the N1 in various temporal and strength measures, though less prominent than that observed for characters. In the P2 and P3, unlike the earlier character-pseudocharacter differences that were all obtained in the LH, differences between these two stimulus types were all observed in the RH. This may indicate that the RH started to get more involved in later stages of character processing, which supports the speculation based on behavioral results. It is worth noting that Kim and Kim (2006) also reported a left-to-right shift in hemispheric lateralization by using

Korean subjects and Korean stimuli. Specifically, they found that brain activation was first left-lateralized in the N1 and more importantly that right-dominant activities became prominent in later stages (P3, LPC). Taken together with findings in the present study, it seems to suggest a more general RH involvement in the processing of compact square-like characters (Chinese and Korean).

#### 7.5.2.3 Effect of eccentricity and the 'unilateral vs. bilateral projection' dispute

As noted in the Introduction section of this chapter, there exists a distinction between 'exogenous' and 'endogenous' ERPs in the literature. The former refers to those early visuo-perceptual components which are more prone to changes in the physical characteristics of visual input, such as eccentricity and exposure duration of presentation, and the latter refers to those later cognitive components which are more associated with cognitive factors such as stimulus type and task difficulty. However, such distinction is not clear-cut. Findings of the present study clearly show that eccentricity influenced participants' cortical response throughout the 500-ms EEG epoch as well as participants' behavioral response later on and this influence interacted with stimulus type from the initial stage of stimulus processing.

The earliest effect of eccentricity in the present study was observed during the POI of 60-100 ms for characters in the RVF. Specifically, only the RX-presented characters elicited the same microstate topography (ContrP1) as their foveal counterparts whereas the topographies of other extrafoveal conditions all lagged behind their foveal counterparts to different extents showing either the C1 activations or a concurrence of fading C1 and rising ContraP1. As discussed earlier, this observation reveals an early interaction between visuo-anatomical constraints and top-down stimulus-specific influences in the temporal domain of the ERP response to characters and character-like stimuli. The foveal part of the retina is characterized by a high

concentration of cone photoreceptor cells which gradually become sparser towards the periphery where rod cells are more populated. There is evidence that cones respond to stimuli faster than rods (e.g., Kandel, Schwartz, Jessell, 2000). It is therefore reasonable to assume that visual input presented within the fovea is sampled with more cones and therefore reaches the primary visual cortex more quickly than extrafoveal input. The synchronization of microstate topography during the POI of 60-100 ms between the RX\_Ch and RF\_Ch conditions therefore suggests that the visual pathway in the LH may be language-sensitive enough to speed up the relay of extrafoveal character stimulation at 2deg in the RVF from the retina to the visual cortex as to 'catch up with' that of foveal character stimulation at 0.15deg in the same visual field. (refer back to discussion for the 60-100 ms microstate and Figure 7.8 for details). Immediately following the POI of 60-100 ms, the contralateral P1 for extrafoveal presentations appeared between 100-140 ms. Although no statistical analysis was performed for the topographic GFP measures during this time window, a VisField\*Eccentricity interaction in the P1 peak latency revealed that P1 peaks for LX presentations were still significantly delayed compared to LF presentations. This indicates that, further to the POI of 60-100 ms during which only RX-presented characters elicited the same microstate topography as their foveal counterparts, processing of extrafoveally presented Ps and VM stimuli were also able to 'catch up with' that of their foveal counterparts only when they were projected from the RVF to the ipsilateral LH. In contrast, processing of extrafoveally presented stimuli in the LVF still lagged in the contralateral RH compared to their foveal counterparts from the same visual field.

Latency shift between the two eccentricities also appeared in later stages of character and pseudocharacter processing. However, it is important to note that these later eccentricity differences showed the opposite pattern and were of a distinct nature.

As discussed above, eccentricity-related latency shifts during the initial stages could be attributed to the human visual anatomy so that extrafoveal presentations reached the primary visual cortex later than their foveal counterparts and thus resulted in the delay in their ERP responses which was then overcome at different points of time for different extrafoveal conditions until it disappeared by the end of IpsiP1 (synchronization to its corresponding foveal condition first found for RX\_Ch in the C1, then for RX\_Ps/VM in the ContraP1, and lastly for all LX presentations in the IpsiP1). In contrast, eccentricity effects on the temporal properties of ERPs which re-appeared from the IpsiN1 onwards could be attributed to differential perceptual evidence accumulation processes for foveal and extrafoveal presentations. Specifically, the IpsiN1 topography (180-200 ms) in response to foveal presentations in the RVF reached its MaxGFP at a later point of time compared to their extrafoveal counterparts (refer back to panel A, Figure 7.12). As noted in above discussion for the N1, the foveal retina, compared to the extrafoveal retina, is characterized with higher cone density and smaller receptive field size and therefore is more capable of processing visual information of higher spatial frequencies, which is the main task of the N1. When stimulated from the RVF, the advantage of fovea sampling in terms of providing greater amount of eligible perceptual material for the P-dominant N1 analysis could be better utilized in the LH and the finer stimulus features including strokes and stroke features could be processed to a greater extent, which was reflected in the significantly delayed topographic TFMMaxGFP in response to RF stimuli relative to RX stimuli when information flow was relayed to the ipsilateral hemisphere. The influence of such differential perceptual evidence accumulation processes persisted through the subsequent ERPs which all featured delay in some or all temporal measures of ERP response to foveal presentations relative to extrafoveal presentations (delayed onset, TFMMax, offset of the P2 microstate topography in

response to foveal presentations as shown in Figure 7.12; delayed TFMax and onset of the P3 microstate topography in response to foveal presentations as shown in Figure 7.14; delayed onset of the N400 map in response to foveal presentations as shown in Figure 7.16).

The above paragraphs discussed how foveal and extrafoveal presentations elicited ERP differences in the temporal and the strength (local and global) domains. Recall that one of the motivations for the present study was to investigate the dispute between the 'unilateral vs. bilateral' views of foveal processing, namely, whether stimuli presented in either visual field within foveal vision initially project to the contralateral hemisphere only or to both the contralateral and the ipsilateral hemispheres (as mentioned in Sections 6.5, 7.2.3 and 7.2.4). The peak analysis of the ERP data found a split pattern of P1 peak latency for stimuli in either visual field regardless of eccentricity. Specifically, the P1 in response to LVF stimulation first peaked in the RH and then in the LH with a mean delay of 34 ms and vice versa with a mean delay of 44 ms. This is consistent with the directional asymmetry in interhemispheric transmission time that right-to-left interhemispheric transfer is faster than left-to-right interhemispheric transfer (e.g., Brown & Jeeves, 1993; Brown, Larson & Jeeves, 1994; Saron & Davidson, 1989). The 34-44 ms interhemispheric delay is also similar to the 26-43 ms delay reported in ERP studies using English words as stimuli (e.g., Martin et al., 2007). Although the observation of 34-44 ms interhemispheric transfer time in the present study seems to support the 'unilateral projection' view of foveal processing, there are three important points to note when interpreting this finding.

First of all, the delay between the contraP1 and the IpsiP1 peaks found here cannot be taken as evidence for the argument that the human fovea is precisely vertically split in the middle. The observation of an early contraP1 and a late IpsiP1 was

made by presenting foveal stimuli at 0.15 degrees away from central fixation. Indeed, this observation does not rule out the possibility that there exists an overlap of contralaterally- and ipsilaterally-projecting cells along the vertical centre of the fovea and this vertical strap of overlapping cells is constrained within 0.15 degrees to either side of fixation point.

Secondly, despite that foveal and extrafoveal presentations both elicited asynchronized P1 peaks in the two hemispheres, it is important not to overlook how they can interact with visual field and stimulus type to result in different brain responses at the same time. For example, a visual field difference was observed when stimuli were presented extrafoveally with the overall P1 peak latency being shorter for RVF stimuli compared to LVF stimuli; in contrast, there was no such visual field difference within the fovea, which implies that characters and character-like stimuli presented within the fovea are less likely subject to the influence of hemispheric asymmetries

Another important point to consider when addressing the 'unilateral vs. bilateral projection' issue is whether the initial unilateral projection has significant impact on lexical processing or the ultimate behavioral responses. There are two aspects to the question, namely, at what stage lexical processing of Chinese characters takes place and whether ERP results (or more generally neurophysiological results) and behavioral results are always consistent with each other, which will be discussed in the following two sections, respectively.

#### 7.5.2.4 Timing of lexical activation

The timing of lexical activation remains one of the most investigated issues in ERP studies of word recognition. A common strategy has been used in these studies (as well as the present study) to identify processes specifically involved in the encoding of words or linguistic stimuli is to compare the ERP responses to words and other

perceptually similar but non-linguistic stimuli (such as pseudowords or nonwords) and look for the time points of ERP differences. As introduced in Section 7.2.2, ERP differences between words vs. word-like stimuli or characters vs. character-like stimuli have been found in all major components from the P1 to the N400, though not all in the same studies. Researchers have different views towards at what stage these ERP differences reflect lexical processes. Depending on the latency of ERP divergence associated with lexical processing these different views can be categorized as the 'early latency' view, the 'mid latency' view and the 'late-latency' view, which argue that lexical activation takes place in the P1 (~ 100-150 ms), in the N1 or P2 (~ 150-250 ms) and in the P3 (~ 300-350 ms) (refer back to Section 7.2.2 for references). Note that the N400 is generally agreed to reflect semantic processing given its late latency which is close to behavioral responses and its exclusivity to meaningful stimuli (as a whole or in part).

A major reason which may have contributed to the confusion over the timing of lexical activation is the lack of appropriate benchmark conditions in the existing studies when comparing words and pseudowords/nonwords. As noted above, it is common to determine processes involved in lexical activation by comparing ERP responses to words against responses to word-like stimuli. However, when investigating English word recognition, almost all existing studies compared words against only pseudowords or nonwords or characters against only pseudocharacters or noncharacters when investigating Chinese character recognition. Consequently, without an appropriate benchmark condition for word-pseudo/nonword or character-pseudo/noncharacter comparisons, it is more likely to mistake an ERP difference due to processing of visual features as reflecting lexical activation, especially in very early components which are known for their sensitivity to physical characteristics of stimuli. To help offset the

ambiguity, the present study introduced the VM condition which were visually matched to characters with equal amount of visual contents in almost the same overall contour. Since VMs and pseudocharacters were related to characters in different ways, the former being more visually matched whereas the latter showing greater orthographic validity, the present study would be able to draw more informed conclusions as to the nature of early ERP variations between stimulus types.

In the present study, the earliest ERP modulations due to stimulus type was obtained during the POI of 60-100 ms. In the temporal domain, a latency shift caused the topographic configuration differences between the RX\_Ch versus the RX\_Ps and the RX\_VM conditions. Specifically, topographic configurations in response to foveal stimuli featured mature ContraP1 activities. These topographies were ahead of the topographies for extrafoveal stimuli (C1 for the LX stimuli and co-existence of C1 and rising ContraP1 for the RX stimuli) except that characters presented in the RVF elicited the same topographic map at both eccentricities (refer back to Figure 7.8). As discussed in proceeding sections, the general trend of earlier ContraP1 topography for foveal stimuli compared to extrafoveal stimuli may be explained by the visual anatomy of the human retina in that the fovea contains a higher population of cone photoreceptor cells which respond to stimuli faster than rod cells (Kandel, Schwartz, & Jessel, 2000; Schlykova, van Dijk, & Ehrenstein, 1993). However, the synchronization of the ContraP1 topography and consequently the overall P1 peaks between the RX\_Ch and RF\_Ch conditions suggests that the visual pathway in the LH may be language-sensitive enough to speed up the relay of extrafoveal character stimulation at 2deg in the RVF from retina to the visual cortex as to 'catch up with' that of foveal character stimulation at 0.15deg in the same visual field.

ERP modulations due to stimulus type were also observed in the strength

domain during the POI of 60-100 ms with weaker MeanGFP for characters compared to pseudocharacters. In a similar vein, results of the peak analysis also showed lower P1 peaks for characters than for pseudocharacters. As noted in Section 7.2.2, Hauk et al. (2006b) and Sereno et al. (1998) both reported similar pattern of stronger P1 activations for words relative to pseudowords and/or nonwords. Hauk et al. interpreted this early ERP strength modulation as certain typicality effect whereas Sereno et al. argued that it reflected very early lexical activations. Indeed, without a benchmark condition which is more visually matched to words than nonwords, it is difficult to determine the nature of the difference between words versus pseudowords in the P1 which is known for its sensitivity to physical characteristics of stimuli.

Indeed, apart from the above-mentioned character-pseudocharacter differences, the present study also found that characters and VMs produced similar level of MeanGFP over the POI of 60-100 ms and P1 peak amplitude. Given that VMs maintained the overall contour features of characters and that the magnocellular P1 has been associated with processing of coarse-scale configurational information (refer back to P1-related part in Section 7.5.1 for details and references), the character-pseudocharacter differences observed in this early stage is more likely to be visuoperceptual in nature rather than reflecting lexical processing.

Now that the ERP differences between characters and character-like stimuli during the P1 time window have been shown to be mainly visuoperceptual, it is important to determine the nature of stimulus type differences in later ERPs. The N1 and the P2 are the mid-latency ERPs which have been mostly associated with lexical processing.

In the N1, both global (MeanGFP and MaxGFP) and local (peak amplitude) measures showed a main effect of stimulus type with stronger cortical responses to

characters relative to VMs. Besides, characters did not differ significantly from pseudocharacters except in the RF location. There are two possible interpretations for this pattern of results. Firstly, it may imply that the N1 is responsible for analyzing fine-scale stimulus features, which is consistent with the long established finding that the N1 is specially tuned to parvocellular processing. The fact that pseudocharacters also contained valid higher-spatial-frequency information such as strokes (in various angles) and stroke clusters may have caused the absence of character-pseudocharacter difference except in the RF location. Note that the RF location was where the peak amplitudes for characters differed from those in response to pseudocharacters in the proceeding stage (the P1), which may indicate that the coarse-scale configurational information of characters was more readily extracted in the fovea where better visual acuity is available and then better processed in the LH which has been shown to be more sensitive to characters and character-like stimuli (refer back to P1-related part in Section 7.5.1 for detailed discussion).

An alternative interpretation of the stimulus effects in the N1 peak amplitude is that the N1 involves more than one brain process, with fine-scale feature analysis being the major part and some extent of lexical processing at the same time. Indeed, it is unlikely that an ERP component is exclusively restricted to only one processing task, especially in early stages when neural oscillations have not settled into flatter slow-wave activities. Recall that the P1 and the N1 were introduced earlier as the M-pathway and the P-pathway components, respectively. The 'M-pathway' and 'P-pathway' tags are only meant to emphasize that the P1 is more tuned to low-spatial-frequency information and the N1 is more sensitive to high-spatial-frequency information; it by no means rules out the possibility that some high/low-spatial-frequency information is also processed in the P1/N1 at the same time. A case in point is the finding in the present study that the

topographic patterns during the POI of 60-100 ms in response to extrafoveal presentations lagged behind their foveal counterparts except for characters presented in the RX and the RF locations. If the P1 did not involve any sort of feature analysis at all, the visual system should not be able to differentiate RX\_Ch stimuli from RX\_VM stimuli as to selectively speed up information relay from extrafoveal retina to primary visual cortex.

Immediately after the N1, P2 responses also varied with stimulus type. Specifically, characters and pseudocharacters elicited stronger P2 activation locally (peak amplitude) and globally (microstate MeanGFP and MaxGFP) than VMs. More importantly, pseudocharacters elicited stronger P2 than characters in the RH when they were presented in the RVF. There are indications from several aspects that associate the P2 with lexical processing of Chinese characters.

The first aspect to consider is the P2 strength. As mentioned earlier in the overview of neurophysiological studies investigating Chinese character recognition, the earliest character-pseudocharacter difference was reported during the time window of 200-250 ms with pseudocharacters eliciting a greater positivity than characters (Wang et al., 2010). Although the character-pseudocharacter difference during the P2 time window in the present study was significant only for RVF presentation in the RH, the direction of the difference and the time window are both consistent with the finding in Wang et al. (2010). This consistency may suggest that the P2 is a crucial stage of processing in Chinese character recognition.

Another key study in the literature that established the P2's role in the lexical processing of Chinese characters is Liu et al. (2006) which investigated how Chinese learning experience as a second language changed the N1 and the P2 responses. They found that native speakers of English showed stronger N1 and P2 in response to

Chinese characters relative to English words after one-term learning of Chinese; moreover, the N1 difference between the two languages was eliminated whereas the P2 difference remained at the end of the second term. Liu et al. proposed that results at the end of the first term reflected that more visual analysis (occipital N1) and lexical access (centrofrontal P2) demand and effort was needed for processing Chinese characters. The finding that character-word difference persisted in the P2 while it was eliminated in the N1 at the end of the second term was believed to indicate that character reading remained a demanding task at the lexical access level while visual analysis had been quickly accommodated.

Another study worth mentioning is Kim and Kim (2006) which compared ERP responses of native speakers of Korean to Korean, Chinese and English words and found a numerical trend of highest P2 amplitude for Chinese words, intermediate for Korean words and lowest for English words. Although not a significant language effect, the pattern found in Kim and Kim (2006) is similar to the trend observed in the present study in that they both feature intermediate P2 strength in response to participants' native language (Korean words in Kim & Kim and characters in the present study) with native-like stimuli (Chinese words and pseudocharacters, respectively) eliciting greatest P2 activation and non-native-like stimuli (English words and VMs, respectively) eliciting the lowest P2 activation. These findings all seem to associate the P2 strength with the effort needed for retrieving the lexical representation for a particular input item. In line with the argument of Liu et al. (2006) mentioned above, stronger P2 activation in response to pseudocharacters may reflect their status as 'potential' character candidates, granted by their orthographic validity, which accordingly caused confusion and hence demanded more searching and matching workload; in contrast, the observation of lowest P2 amplitude for VMs seems to imply that they were more readily rejected and

the lexical retrieval process for this type of stimuli ended with less effort. More evidence in support of this speculation is to be provided below from the aspect of topographic pattern during the P2 time window. Indeed, a more general opinion along the similar line is that the P2 may be part of some cognitive matching system that compares perceptual inputs with mental representations either stored in memory or built from a linguistic context (Curran & Dien, 2003; Evans & Federmeier, 2007; Federmeier, Mai, & Kutas, 2005; Luck & Hillyard, 1994; Misra & Holcombe, 2003, etc.).

A second aspect to consider is the P2 topographic pattern. Although the same topographic maps was identified for characters, pseudocharacters and VMs, the map offset for the VM condition was significantly earlier compared to characters and pseudocharacters (refer back to Figure 7.9 and Figure 7.12). If the P2 is where lexical activation is attempted, a longer-lasting P2 topographic pattern with stronger global and local strength in response to characters relative to VMs may suggest that lexical access was attempted for VMs which was unsuccessful and hence ended sooner.

Last but not least, consider the source areas responsible for the P2 cortical activations. Source estimation identified the Brodmann area BA9 in the frontal gyrus as responsible for the P2 differences between characters and VMs in foveal presentation. There exists evidence from fMRI studies that the BA9 area plays an important role in Chinese character recognition. For example, Liu et al. (2008) compared BOLD (blood oxygen level dependent) in response to centrally presented characters, pseudocharacters and artificial characters (random combination of incomplete radicals). They observed greater brain responses to characters and pseudocharacters relative to artificial characters not only in the left fusiform gyrus, an area typically associated with visual form analysis of English words, but also in the middle frontal gyrus (BA9) which has not been reported as often in studies using English words as stimuli. Liu et al.

speculated that the BA9 area might be an indispensable part of a neural circuit for orthographic-semantic transfer in Chinese character processing.

To sum up, evidence from the aspects of ERP strength, topographic pattern and source area all suggests that the P2 plays an important role in the lexical processing of Chinese characters. Considering evidence from eye tracking studies that gaze duration in Chinese sentence reading lasts around 260 ms (e.g., Li, Liu, & Rayner, 2011; Yan & Bai, 2000), it can be inferred that lexical activation when reading Chinese characters completes by the end of the P2, regardless whether the N1 is partially involved or not.

Linking back to the questions raised at the end of proceeding section that whether the initial unilateral projection from retina to primary visual cortex had an impact on later processes of foveally presented characters, it can be concluded that the initial unilateral projection affected the lexical processing of foveally presented characters given the above discussion that lexical processing of Chinese characters mainly takes place in the P2 with possible start in the N1 and the observation of VisField\*Hemisphere interaction effects in the N1 and P2. The following section will discuss the question of whether patterns observed in ERP results, especially in early stages, are necessarily consistent with the ultimate behavioral results.

#### 7.5.2.5 Consistency between behavioral and ERP results

Recall that the major motivation of using the ERP technique to investigate if character recognition and the character superiority is affected by the visual field and eccentricity of presentation was because behavioral responses are the outcome of a sequence of complex brain processes and do not provide direct answer to the question that whether characters foveally presented to either side of the fixation point initially project to the contralateral hemisphere or both hemispheres. Now that ERP results of

the present study show an unilateral projection pattern for laterally presented stimuli both within and outside the fovea and the influence of this unilateral projection at the initial stage lasted through the lexical processing in the P2 (see discussion above), the question remains whether the ultimate behavioral responses would show traces of this influence.

Behavioral results based on accuracy data showed no visual field or eccentricity effect on the recognition of characters, pseudocharacters or VMs and accordingly the same size of character superiority foveally and extrafoveally in both visual fields. In addition, behavioral results based on RT data also showed that presenting characters foveally or extrafoveally in the LVF or the RVF had no significant impact on how fast participants responded to characters. These behavioral results seemingly contradict the ERP finding that character processing showed hemispheric asymmetry from the very start (C1). The following paragraphs will explain that the 'inconsistency' is only superficial in this case and more importantly make the point that behavioral and ERP results are not always consistent with each other in all respects with examples from relevant literature.

The absence of visual field effects on character recognition, even when presented for merely 17 ms outside the fovea, supports the argument that the two hemispheres play a balanced or equivalent role in Chinese character recognition. However, it is hard to determine whether the two hemispheres are equally involved throughout all stages of character processing or there do exist hemispheric asymmetries the pattern of which may vary along the time course. The latter hypothesis was confirmed by the ERP results which revealed a left-to-right shifting trend between the two hemispheres. Specifically, the LH appeared to play a more dominant role in early stages of character processing when the visual information of stimuli was analyzed (up

till ~ 200 ms) whereas the RH started to get more involved from the mid-latency component P2 towards the N400 when higher-order properties of characters were processed (refer back to Section 7.5.2 for detailed discussion on hemispheric asymmetries). Therefore, it can be claimed that behavioral results of the present study are consistent with ERP findings on the issue of hemispheric asymmetries in Chinese character processing in that hypothesis based on behavioral results gained support from ERP evidence.

Despite the above discussion, it is important to understand that behavioral and ERP results are not always consistent with each other in all respects and this inconsistency can be a natural consequence of the complex, dynamic, and flexible nature of the the human brain.

There are five major components within the first half second post stimulus onset that are commonly reported in language-related ERP studies, namely, P1, N1, P2, P3 and N400. The present study was even able to analyze ERP data before 100 ms by employing the electric neuroimaging technique. Each of these individual processes has its own characteristics in stimulus processing (e.g., hemispheric asymmetry) while being subject to influences of previous components. In consequence, ERP patterns observed in early stages might change over time and eventually bear little or no mark in behavioral results. For example, Evans and Federmeier (2007) examined the time course of hemispheric asymmetries in verbal memory with an old-new judgement task. They found three ERP memory effects which all featured a right lateralization; in contrast, the behavioral results clearly showed the classic RVF advantage over LVF in English word recognition which is typically taken as evidence for a left-lateralized neural network for word processing.

On the other hand, effects observed in behavioral results may not be present in

all ERPs not only because behavioral response is the ultimate outcome which does not necessarily agree with the output of each individual component but also because certain vulnerable effects simply may not be observable in all components (especially the earlier ones). Indeed, as Barber and Kutas (2007) remarked, whether the brain distinguishes between certain types of input depends not only on the nature of these inputs but also on factors such as visual parameters, task demand, experimental design, and stimuli composition whereas behavioral effects are more likely to withstand these variations. For example, behavioral results of the present study showed the character superiority over pseudocharacters irrespective of the visual field or eccentricity of presentation whereas the ERP differences between characters and pseudocharacters were always moderated by the factors of visual field and eccentricity before the N400. Another example of ERP effects' sensitivity to visual parameters is Martin et al. (2006) which compared ERP responses to words and pseudowords in the P1 and the N1 by using two stimulus exposure durations (55 and 66 ms, respectively). Their behavioral results showed a WSE under both duration conditions whereas the N1 difference between words and pseudowords was only observed when the longer duration was used. More relevant examples of such inconsistency include studies which found no ERP indications of hemispheric asymmetries despite a robust RVF advantage obtained with behavioural measures (e.g., Federmeier, Mai, & Kutas, 2005; Evans & Federmeier, 2009).

In summary, ERP findings of the present study show that character processing featured hemispheric asymmetries from the very start with the LH being more specialized than the RH as the initial-receiving hemisphere. However, this initial visual field and hemispheric difference was not directly reflected in behavioral results which imply that the two hemispheres are involved in character processing in a more balanced

manner, as opposed to the prominent RVF/LH advantage in English word recognition. Given how hemispheric lateralization pattern changed along the time course (shifting from left to right), the absence of visual field effect in behavioral responses to characters can be considered as consistent with the ERP findings. However, behavioral and ERP results showed inconsistency in the respect of whether character-pseudocharacter difference was moderated by visual field and eccentricity with the ERP effect of stimulus type being more sensitive to manipulations of visual parameters. This inconsistency, like those reported in other studies, reflects the complexity, flexibility and dynamics of the the human brain. Indeed, as Evans and Federmeier (2009) remarked, it is the inconsistency between behavioral and ERP results that highlights the need to treat different stages of word (and character) processing as distinct.

## Chapter 8. General Discussion

### 8.1 Summary of findings

#### 8.1.1 Experiment 1: Determining the optimal retinal image size in normal Chinese reading

As indicated by the title of the thesis, the research question at the centre of the thesis was the WSE in Chinese and how this effect in central and lateralized display can help reveal the processes involved in Chinese character recognition. Before that, Experiment 1 was conducted to establish the optimal retinal image size in normal Chinese reading, which is fundamental to any studies investigating Chinese character recognition and Chinese reading in general yet has never been researched before.

The viewing distance at which standard Chinese textual material was presented was manipulated. Reading rate results revealed a 6-range performance pattern, namely, 2.5 cm, 5.0 cm, 7.5-55.0 cm, 57.5-70.0 cm, 72.5-90.0 cm, and 92.5-100.0 cm. The mid range of 7.5-55.0 cm was considered as the optimal viewing distance range for normal Chinese reading due to the finding that distances within this range only produced consistently better reading performance compared to distances at the two extremes (2.5 cm and 92.5-100 cm). Regression analysis revealed that a maximum mean reading rate of 494 characters per minute (cpm) occurred at approximately 35.0 cm, suggesting a visual angle of 0.5 degrees for each character.

Previous studies investigating Chinese text reading and character recognition have all used randomly selected retinal image sizes or viewing distances for stimuli presentation. Indeed, findings of the present experiment have important implications for understanding the visual processes involved in character perception. Firstly, the 7.5-

55.0 cm distance range sheds light on what spatial frequencies are key to efficient Chinese reading. Indeed, characters in standard book publication typeface (Song, 10.5 pt) presented within this optimal distance range subtended visual angles between 2.3 degrees and 0.3 degrees, which resembles the observation in Legge et al. (1985) that maximum reading rates were achieved for characters (letters) subtending between 2.0 degrees and 0.3 degrees. Moreover, within this optimal range, spatial frequencies corresponding to overall character width were between approximately 0.2 and 1.6 cpd and these are low spatial frequencies that the magnocellular pathway is most sensitive to. Besides, when characters were presented at 35.0 cm, the optimal reading distance suggested by the regression model, characters featured a spatial frequency band of approximately 1-10 cpd. The fact that the centre frequency of this band, 3.2 cpd, is near the peak of the spatial contrast sensitivity function of human vision suggests that the optimal reading distance of 35.0 cm is where visual information of characters is scanned around spatial frequency that human eyes that are most sensitive to. Secondly, the distance range of 7.5-55.0 cm may be better suited to producing the eye movement patterns that are essential to efficient Chinese reading.

As mentioned above, the regression model revealed an optimal viewing of 35.0 cm for reading common Chinese textual material. When viewing from this distance, each character subtended a visual angle of 0.5 degrees. Experiments in following chapters were all guided by this viewing distance and its associated retinal image size for a more precise assessment of the WSE in Chinese.

### 8.1.2 Experiment 2: Character and pseudocharacter superiority investigated with inversion of stimuli

Experiment 2 was the first attempt of the present thesis to reassess the character superiority effect. Four stimulus conditions were examined, namely, characters,

pseudocharacters, inverted characters, and visual matches (VMs) of characters, using the Reicher-Wheeler task. Experiment 2 failed to observe any character superiority effect over pseudocharacters whereas both stimulus conditions produced better identification performance compared to inverted characters and VMs.

The character superiority over inverted characters (12% accuracy difference) was similar to the inversion effect previously reported in Chinese character recognition (e.g., 15% accuracy difference in Kao, Chen, & Chen, 2010). However, the finding of both character and pseudocharacter advantage over inverted characters without character advantage over pseudocharacters brings the confounding that the character advantage over inverted characters may have been the consequence of inversion effect on the whole character basis or on the individual radical basis. Possible explanations for the failure to observe a character superiority over pseudocharacter were discussed. Compared to Cheng (1981) which also used a two-alternative forced choice task and found the WSE in Chinese, Experiment 2 differed in the following ways. Firstly, the Reicher-Wheeler task used in the present experiment had more stringent and sophisticated design than a regular two-alternative forced choice task (refer back to Section 4.1 for details). Secondly, stimuli in Cheng (1981) spanned a visual angle of 2 degrees, which was considerably larger than the optimal retinal stimuli size (0.5 degrees) for normal Chinese reading, as suggested by findings of Experiment 1. Another distinct difference between the Experiment 2 and Cheng (1981)'s study lies in the stimulus exposure duration. The mean stimulus exposure duration was 12.43 ms in Cheng (1981) whereas the present experiment used an exposure duration of 17 ms. Indeed, one possible reason for the absence of the character superiority effect in the present experiment is that more limited visual access to stimuli may be necessary for the effect to show through, which motivated Experiment 3.

### 8.1.3 Experiment 3: Character superiority over pseudocharacters investigated with backward Masking

There exists evidence in the literature that the word superiority effect is more prominent in more severely data-limited viewing conditions. Among the various ways to increase the visual difficulty of the task, reducing stimulus exposure duration and using masking can both fulfill the requirement while maintaining the natural appearance of characters as they would be encountered in everyday reading. However, an average identification accuracy of around 75% across stimulus conditions in Experiment 2 showed that 17 ms was an appropriate stimulus exposure duration and using shorter durations may produce a floor effect. Therefore, Experiment 3 of the present thesis examined the character superiority over pseudocharacters by using visual masks.

The results showed that backward pattern masking seemed to have impaired identification performance for VMs (2% increase of error rate shown as significant by an unpaired Welch-corrected *t*-test; refer back to Section 5.3 for details) but not for characters or pseudocharacters. This may have been due to the fact that masks were composed of very fine-grained high spatial frequency features (stroke fragments) which may not be able to exert any significant interference on the extraction and analysis of more coarse-scale low frequency information in characters, pseudocharacters and inverted characters when they were presented only for 17 ms. Failure to observe significant character superiority effect over pseudocharacters in two consecutive experiments presented two directions of follow-up investigation. One route to take was to press on with visual masking by increasing mask presentation time, by making new masks that share greater visual similarity to characters and pseudocharacters, or by combining both. However, limiting visual access is only a tool of establishing the WSE of characters over pseudocharacters in Chinese character recognition, i.e., by observing

differentially impaired character and pseudocharacter perception. An alternative route was to reconsider the assumption of the WSE in Chinese. If Chinese radicals were indeed processed individually regardless of context lexicality, then no significant WSE for characters should be observed not only when compared to pseudocharacters but also when compared to other non-lexical context conditions, which motivated Experiment 4.

#### 8.1.4 Experiment 4: Character superiority over pseudocharacters investigated with semi-inversion of stimuli

Experiment 4 further investigated the character superiority effect over pseudocharacters with changed stimulus conditions. Specifically, the non-critical radicals in characters and pseudocharacters used in Experiments 1-3 were inverted to create two new nonlexical contexts for radical perception. These two semi-inverted conditions were analogical to the single letter condition in studies investigating the English word-letter effect. Besides, since it was well-established in the two preceding experiments that the VM condition provided a more inferior context for radical discrimination compared to characters, pseudocharacters, and inverted characters, the VM stimuli were replaced by inverted pseudocharacters which was expected to serve as a better control condition.

The most important finding of Experiment 4 was the significant character superiority effect over pseudocharacters, which supports the argument that the lexicality of the context in which a radical is contained affects its recognition. For pseudocharacters, the 'made-up' combination of component radicals means that the complete outline (not just the left-most and the right-most margins), the spatial arrangement of strokes from either radical at the top and the bottom, and the inter-radical interactions have never been encountered before and have no representations in the visual system. In contrast, such coarse-scale configurational information in

characters is familiar to Chinese readers and therefore is highly utilizable to efficiently determine character identities.

Possible reasons for obtaining significant character superiority over pseudocharacters in Experiment 4 but not in Experiments 2 and 3 were discussed. Apart from that Experiment 3 used visual masking whereas Experiments 2 and 4 did not, these three experiments only differed in sample size and stimuli composition. There exists evidence in the literature that changing stimuli composition and accordingly participants' expectation towards the frequencies of different stimulus conditions may affect participants' responses (e.g., Carr et al., 1978). However, since participants' subjective expectation was not manipulated and, more importantly, the change in stimuli composition did not affect how well participants responded to characters or pseudocharacters compared to the two preceding experiments, it was argued that increased sample size rather than changed stimulus conditions in Experiment 4 had caused the different results between the present experiment and previous two attempts. The sample size account was further supported by results of Experiment 5.

The discrepancy in the size of character superiority over pseudocharacters between Experiment 4 (3%) and previously reported character superiority (8%, Cheng, 1981) over pseudocharacters may have been caused by the extremely short stimulus exposure duration used in previous studies. When compared to findings in studies using English stimuli, the size of character superiority over the pseudocharacter and single-radical conditions seemed considerably small and there was no counterpart effect for the pseudoword superiority over single letters for pseudocharacters. One possible explanation for these discrepancies is the compositional differences in terms of number of lower-level components between Chinese stimuli (containing two radicals) and English stimuli (containing four or more letters). Another possibility is that the

relatively smaller character superiority effect and the absence of pseudocharacter superiority effect reflect certain language-specific mechanism in the processing of Chinese characters and character-like stimuli.

Finding of Experiment 4 provided a straightforward motivation for the next experiment, i.e., to investigate if the character superiority also exists with lateralized presentation and if the visual field (LVF or RVF) of presentation has significant impact on the processing of characters and character-like stimuli.

#### 8.1.7 Experiment 5: Character superiority over pseudocharacters in lateralized display and its neural correlates

Experiment 5 combined behavioural and ERP measures to investigate the following aspects of Chinese character recognition. First of all, the experiment aimed to determine if there exists behavioural and/or ERP evidence of context effects in lateralized Chinese character recognition, namely, if the context (e.g., character, pseudocharacter, VM) in which the visual contents of a character affects participants' behavioural and/or ERP response. Secondly, it aimed to examine if the two hemispheres show any pattern of asymmetry or lateralization when processing Chinese characters and furthermore if the same pattern appears for both foveally and extrafoveally presented characters. Thirdly, the experiment attempted to provide estimations on a spatiotemporal profile of cortical character processing based on findings from the first two questions, e.g., the points of time when and the brain areas where ERP responses differ between stimulus types, visual fields, and hemispheres.

Analysis of response accuracy and time data showed no effect of visual field or eccentricity on character identification. Besides, a character superiority in terms of response accuracy over pseudocharacters and VMs was obtained irrespective of visual field and eccentricity, though the character superiority in terms of response time over

pseudocharacters was not significant in the RX position due to improved performance of pseudocharacters. Absence of visual field effect on character recognition, even with merely 17 ms exposure duration outside the fovea, supports the argument that the two hemispheres play a balanced or equivalent role in Chinese character recognition. However, it is hard to determine whether the two hemispheres are equally involved throughout all stages of character processing or there do exist hemispheric asymmetries the pattern of which may vary along the time course. The latter hypothesis was confirmed by the ERP results which revealed a left-to-right dominance shifting trend between the two hemispheres.

Although the behavioural effect of character superiority was independent of visual field and eccentricity, these two presentation parameters modulated ERP effects of stimulus type from the initial stage of stimuli processing. Specifically, during the microstate of 60-100 ms, a distinct topographic pattern was identified for stimuli in each of the four screen locations due to effects of visual field and eccentricity except that characters presented in the RX location elicited the same topographic pattern as their RF counterparts. As introduced in Section 7.2.2, previous studies investigating visual word or character recognition have all discussed the P1 as the first major ERP due to analysis technique constraints and accordingly the earliest ERP effects of visual field and eccentricity were only obtained after 100 ms post-stimulus onset. Using the more recently established electric neuroimaging technique, the present experiment was able to compare ERP waveforms before 100 ms in response to Chinese characters and character-like stimuli for the first time and observed ERP effects of visual field and eccentricity on character processing as early as 60 ms. The latency shift between foveal and extrafoveal conditions at this early stage can be accounted for by the visual anatomy of the human retina that foveal input is sampled with more cone cells and

therefore can reach the primary visual cortex more quickly than extrafoveal input. The synchronization of the ContraP1 topography and consequently the overall P1 peaks between the RX\_Ch and RF\_Ch conditions suggests that the visual pathway in the LH may be language-sensitive enough to speed up the relay of extrafoveal (2 degrees eccentricity) character information in the RVF from retina to the visual cortex as to 'catch up with' that of foveal (0.15 degrees eccentricity) character stimulation in the same visual field. It is important to note that the latency shift between foveal and extrafoveal conditions reappeared in the IpsiN1 in the opposite pattern and then lasted till the P3. It is proposed that this recurrence of latency shift between the two eccentricities, unlike its earlier instance as a result of the visual anatomy, may reflect the outcome of perceptual evidence accumulation in the N1. Specifically, the fovea has more numerous and more active cone cells and therefore can extract fine features of input better than the extrafovea in the ContraN1, which may have resulted in a more packed information flow and accordingly delayed IpsiN1 activities for foveal stimuli.

After the initial stage of 60-100 ms, ERP effects of stimulus on peak amplitude also continued to be modulated by the visual field of presentation and the hemisphere of recording until the POI of 300-330 ms (P3). Specifically, character-pseudocharacter differences were found in the P1 (100-160 ms) peak amplitudes when stimuli were presented in the RF location, in the N1 peak amplitudes in the LH when presented in the LF location, in the P2 (200-250 ms) peak amplitudes in the RH when presented in the RVF, and then in the P3 (300-335 ms) peak amplitudes in the RH. These interaction effects show that the cortical processing of Chinese characters is characterized with different hemispheric lateralization patterns along the time line. More importantly, when considered together with stimulus effects on ERP global strength and on ERP latency measures (refer back to Section 7.4.2 for details), these interaction effects also

help to understand the nature of character processing at various stages.

These ERP findings provide answers to questions left unresolved by the behavioural results. Specifically, the absence of visual field effect on participants' behavioural responses to characters seems to be the ultimate outcome of a sequence of complex brain processes which are characterized with different hemispheric asymmetry patterns. The LH appears more specialized and efficient than the RH in extracting the coarse-scale of characters in the initial stages (C1-P1: 60-160 ms). As noted above and back in various sections in Chapter 7, this observation provided evidence of hemispheric asymmetry in word and character recognition within the first 100 ms post-stimulus onset for the first time. The LH advantage as the initial-receiving hemisphere over the RH continued to influence how the fine features of stimuli are analyzed in the N1 (140-200 ms), which is consistent with the LH dominance typically reported in studies using English words as stimuli. This finding suggests that the LH dominance in processing the visual features of linguistic stimuli may be a universal mechanism involved in both alphabetic and non-alphabetic language processing. Later in the P2 (200-250 ms) and P3 (300-335 ms), the absence of any significant hemispheric difference for characters may suggest that the two hemispheres show equal efficiency in lexical retrieval and equal confidence towards the outcome of internal stimulus evaluation based on perceptual evidence accumulated from previous stages. Compared to the LH specialization shown before 200 ms post-stimulus onset, this may indicate that the RH begins to get more involved in later stages of character processing, which supports the speculation based on behavioral results. Indeed, this provides ERP evidence for the common assumption that the RH plays a more important role in processing Chinese characters relative to English words and is also consistent with ERP findings obtained using other non-alphabetic stimuli (e.g., Kim and Kim, 2006; refer back to Section

7.5.2.2 for detailed discussion).

Last but not least, the observation of distinct microstate topographies for stimuli presented in the LVF and the RVF during the POI of 60-100 ms supports the 'unilateral projection' argument that stimuli presented to either side of central fixation initially project to the contralateral hemisphere. However, since the hemispheric lateralization pattern in Chinese character processing features a shift from left lateralization to no lateralization along the time line, the initial anatomic feature of unilateral projection may not bear any significant influence on the ultimate behavioural responses. This speculation was supported by the absence of visual field effects on participants' response accuracy and time for character stimuli.

## 8.2 Methodological improvements and theoretical contributions towards understanding Chinese character recognition

### 8.2.1 Methodological improvements

Understanding processes involved in visual Chinese character recognition via investigating the character superiority effect is not a new topic. Compared to previous studies, the present thesis benefits from the following methodological improvements.

Firstly task-wise, Experiments 2-5 used the Reicher-Wheeler task to assess the WSE in Chinese. It was pointed out at the beginning of the thesis that the WSE can also be shown in other tasks that are commonly used in the area of word recognition such as naming lexical decision, and other judgement tasks concerning various aspects of stimuli (old/new, same/different, orthographic or phonological similarity, etc.).

However, the Reicher-Wheeler task established by Reicher (1969) and Wheeler (1970) was an experimental paradigm which was specially designed to provide more stringent assessment of the WSE and more accurate understanding of the mechanism behind. In short, the passive viewing mode not only makes it closer to the everyday reading scenario but also overcomes the confounding factors that may occur in tasks demanding extra-perception processing or calculation (such as phonological and decision-making processes); on the other hand, the two-alternative forced choice task and more importantly the sophisticated counterbalancing of the identity and the position of component letters (radicals in this case) across stimulus conditions ensures that better performance in the word or character condition is not due to guesswork based on orthographic knowledge or use of strategy.

Secondly, the present thesis investigated the character superiority effect using properly sized stimuli. The importance of stimulus size is three-fold. Indeed, a stimulus size that is similar to what readers would encounter in everyday reading is generally essential for any experiment aimed at revealing the word or character recognition processes involved in this reading scenario. A more topic-related reason to use appropriately sized stimuli comes from the evidence that the WSE is not observed when English words are presented in considerably large or small sizes, as noted in Section 1.5. Furthermore, proper stimulus size is even more critical for studying lateralized character recognition within the fovea. However, previous studies in the area of Chinese character recognition have all used arbitrarily determined stimulus sizes which range from 0.4 to 11 degrees wide. Therefore, a separate experiment was specially dedicated to establishing the optimal retinal stimulus size for character presentation before the issue of WSE in Chinese was investigated.

The third and fourth aspects in which the present thesis shows more

methodological stringency also relate to studying lateralized character recognition within the fovea and assessing the 'unilateral vs. bilateral projection' debate. Specifically, an eye tracker was used to ensure central fixation. Besides, existing studies in the literature attempted the issue by comparing ERP amplitudes in response to centrally presented SP/PS characters (semantic-phonetic structure and phonetic-semantic structure, respectively). However, as pointed out in Section 7.2.3, it is hardly possible that the component semantic and phonetic radicals in centrally presented SP/PS characters would neatly fall to either side of the fixation point due to the unequal radical sizing and the radical interactiveness features of left-right structured compound characters. In contrast, the present thesis approached the 'unilateral vs. bilateral projection' issue in a more straightforward way by showing characters in their entirety to either side of the fixation point within the fovea and comparing the temporal measures of early ERPs in response to stimulation from either side of fixation.

Furthermore, the present thesis shows methodological improvement in ERP data analysis. Data analysis in existing ERP studies in the area of Chinese character recognition is limited to the conventional peak analysis, which can only reveal cortical response patterns at certain points of time. As a consequence, investigation of ERP components which do not show visible peaks (either due to vulnerability to stimuli's physical characteristics as in early components or more flattened-out waveforms as in later slow wave components) is not possible with the peak analysis. Indeed, all existing studies investigating Chinese character recognition have skipped the C1 due to its weak strength and low incidence and instead described the P1 as the first major ERP after stimulus presentation (refer back to Section 7.1.2 for details). Another limitation of the peak analysis is that it can only analyze ERP responses in one particular cortical area at a time. Experiment 5 of the present thesis overcame these limitations by using the

electric neuroimaging procedure. It not only analyzes ERP waveforms on a point-by-point basis (millisecond by millisecond in this case) which helped data analysis in Experiment 5 cover a more comprehensive time range including the C1, but also provided a global view on cortical activities in response to different experimental conditions.

Last but not least, the present thesis introduced VM stimuli as a benchmark condition which proved to be especially useful in determining the nature of ERP differences between characters and pseudocharacters at various stages. As mentioned in Section 7.2.2, ERP differences between words versus pseudowords in the P1 have been reported in previous studies and researchers have different views regarding the nature of these early effects. Indeed, given that the P1 is known for its sensitivity to physical characteristics of stimuli, it is difficult to determine whether these early effects reflected lexical processing or were only due to visuo-perceptual differences without a benchmark condition which was more visually matched to words than nonwords. The VM stimuli in the present thesis removed the lexicality of characters on the one hand while maintaining the overall spatial configuration and visual intensity (in terms of pixel number and luminance) of characters on the other hand. The observation of similar P1 amplitude in response to characters and VMs as contrasted to pseudocharacters may imply that it was the coarse-scale configurational information that neural system extracts at the P1 stage to differentiate characters from pseudocharacters rather than the higher-order linguistic properties. This takes the categorization effect view a step further that by P1 latency the human brain is not only capable of discriminating visual input of different categories of rather distinct shape, luminance, contrast and spatial frequency spectrum (e.g., verbal stimuli, faces and objects) but also sensitive to overall configurational variations of stimuli under the same category (e.g., characters

and pseudocharacters).

## 8.2.2 Theoretical contributions

Findings of the present thesis have the following contributions towards the theoretical understanding of visual Chinese character recognition.

### 8.2.2.1 Fine-to-coarse vs. coarse-to-fine and feedback vs. feedforward

As introduced in Section 1.2, although existing models of word recognition that explain the WSE differ from each other in one way or another, they all share the common feature of a multi-layer hierarchical structure. The exact number of layers may vary from model to model, e.g., from three layers in McClelland and Rumelhart (1981)'s interactive activation model to seven layers in Dehaene et al. (2005)'s neural code network, nevertheless, they all follow the route from letter features at the bottom (input) layer to letters in the middle layer and finally to words at the top (output) layer. That is, word perception in existing models starts from information at higher spatial frequencies to information at lower spatial frequencies and the WSE is considered as a result of beneficial feedback from activations at the top (word output) layer towards activations at lower levels.

However, ERP evidence in the literature and findings in the present thesis all seem to suggest the opposite pattern, namely, word or character processing in a coarse-to-fine manner. Indeed, evidence from human VEP studies and face perception ERP studies shows that the P1 has a low-pass spatial tuning function and its response depends on a visual pathway preferentially tuned to coarse-magnocellular inputs whereas the N1 is a parvocellular-dominant component being more sensitive to stimulus variations on fine-scale frequencies (refer back to Section 7.5). Besides, neurophysiological studies using macaque monkeys have been able to directly record from individual magnocellular and parvocellular neurons in the lateral geniculate

nucleus (LGN), the primary relay center for visual information received from the retina (e.g., Maunsell, Ghose, Assad, McAdams, Boudreau, & Noerager, 1999). Their results show that signals relayed through the magnocellular layers of the LGN travel with faster conduction speeds than those relayed through the parvocellular layers and consequently magnocellular signals reach cerebral cortex appreciably before parvocellular signals, which further supports the relative timing relationship between M- and P-processing, namely, low-SF M-pathway information gets processed before high-SF P-pathway information.

As argued in Hegd é(2008), visual perception in general is coarse-to-fine in time course. It is unlikely that visual perception of linguistic stimuli would be an exception. Indeed, findings of the present thesis suggest that coarse-scale configurational information in Chinese characters is processed before more fine-tuned features. Specifically, pseudocharacters elicited stronger P1 responses, both locally and globally, than characters and VMs which did not differ from each other. As argued in various sections in the Discussion of Chapter 7 (e.g., Sections 7.5.1.1, 7.5.2.1, and 7.5.2.2), similar level of P1 response to characters and VMs may be explained by the visual similarity between characters and VMs in terms of overall outline and inter-radical spatial relationships, which was familiar to the visual system and accordingly required a relatively low threshold for the neurons to fire; in contrast, these coarse-scale configurational information in pseudocharacters was novel to the visual system and thus less readily extracted, resulting in a higher firing threshold.

In summary, existing models of word and character recognition all describe the higher SF information (namely, letter features, stroke fragments, etc.) as the starting point of the whole process and explain the WSE as the result of facilitatory feedback from the whole word layer in a multi-layer hierarchy. However, this way of structuring

the levels of word or character processing and the 'feedback' account for the WSE are put into question by findings of the present thesis and neurophysiological evidence from the broader area of visual perception which all suggest a coarse-to-fine processing manner. Indeed, the WSE is more likely a result of processing at lower SF levels feeding forward to processing at higher SF levels.

A final point to make here is that the same pattern of P1 differences between characters, pseudocharacters and VMs was observed in both hemispheres, which indicates that the two hemispheres employ the same coarse-to-fine mechanism to process characters and character-like stimuli.

#### 8.2.2.1 The time line of hemispheric lateralization in Chinese character recognition

In contrast to the consistent observation of RVF/LH advantage in English word recognition, investigations into the hemispheric lateralization in Chinese character processing have seen a dispute between three arguments. Using behavioural measures across various tasks, researchers have found no visual field difference, a RVF advantage, and a LVF advantage, which led to the 'LH-dominated' view, the 'RH-dominated' view, and the 'balanced hemispheric involvement' view of character processing, respectively (refer back to Section 7.2.1 for details). The implication of the mixed findings is that the RH seems to play a more important role in Chinese character processing than when reading English words. The main argument for this special role of the RH is based on the differences between English words and Chinese characters, i.e., alphabetic vs. pictographic, linear letter strings vs. two-dimensional compact square shapes. The assumption is that the richer spatial features in Chinese characters require more involvement of the RH which is known for its specialization in spatial processing.

Compared to research using English stimuli, neurophysiological research investigating hemispheric lateralization in Chinese character recognition shows two

distinctive features, a relatively small proportion of ERP studies in the whole research body and consistent area-specific lateralization patterns found in fMRI and MEG studies. The very few relevant ERP studies all reported a RH lateralization whereas the fMRI and MEG findings generally showed left-lateralized activations in the temporal (mainly involving the left middle and posterior fusiform and temporal gyri, BA 37/19) and the frontal (mainly involving the left inferior frontal gyrus, BA 47) cortices in contrast to no hemispheric asymmetries or a right lateralization in the occipito-parietal cortices (refer back to Section 7.2.2 for references and more details).

Behavioural results of Experiment 5 in the present thesis showed no difference between the two visual fields in terms of response accuracy or response time. The absence of any visual field effect on lateralized character recognition, even when presented for merely 17 ms, supports the 'balanced hemispheric involvement' view of lateralized character processing. ERP results of the experiment provide support for this hypothesis. More importantly, these findings show that the absence of visual field effect in behavioural results was an outcome of different hemispheric lateralization patterns balanced over time rather than equal hemispheric involvement through every stage of character processing.

However, in contrast to the conventional assumption that the RH's role in character processing is more manifested in analyzing the visuospatial information of characters (explanation for the observation of LVF advantage or no visual field difference in behavioural studies, as noted above), the visual ERPs in Experiment 5 all showed evidence of a left-lateralization, including the extraction of coarse-scale configurational information during the C1 and the P1 and the analysis of more fine-grained features during the N1. Indeed, it was in later cognitive ERPs that the RH gradually appeared more involved. Specifically, although there was no main effect of

hemisphere in the P2 or the P3, it was in the RH that amplitude differences were obtained between characters and pseudocharacters. As discussed in Section 7.5 (Sections 7.5.1.3, 7.5.1.4, 7.5.2.2, and 7.5.2.4 in particular), stronger responses to pseudocharacters in the RH in these two time windows may be an indication that more efforts and attention resources possibly required when attempting lexical retrieval for pseudocharacters and the brain was more uncertain about the outcome of stimulus processing so far, respectively. During the POI of 450-500 ms (early N400), the microstate topography in response to pseudocharacters featured a left-lateralized negativity, as typically observed with English stimuli; in comparison, the microstate topography in response to characters clearly showed augmented activations in the RH (refer back to Panel A, Figure 7.15), which is consistent with previous ERP findings in the N400. Indeed, the electrode sites that were associated with these hemispheric lateralizations largely corresponded with the brain areas which showed similar hemispheric lateralization patterns in fMRI and MEG studies. Specifically, the P1 and the N1 (occipito-temporal sites) showing the LH dominance agreed with the fMRI/MEG observation of left-lateralized activations in the temporal cortex; greater involvement of the RH in the P3 and the N400 (occipito-parietal sites) was in line with the fMRI/MEG finding of right lateralization in the occipito-parietal areas (refer back to Section 7.2.2 for references and more details).

In summary, findings of the present thesis show ERP evidence that the analysis of visuo-perceptual information of Chinese characters in the earlier stages (C1, P1 and N1) relies more on the activations of the occipito-temporal area in the LH relative to the same area in the RH whereas the processing of more higher-order aspects of characters in later stages requires more participation of the RH, especially in the right centro-frontal (P2) and the occipito-parietal areas (P3 and N400). These findings provide

important time stamps for the area-specific lateralizations observed in fMRI/MEG studies. More importantly, they show that the two hemispheres may play different roles through different stages of language processing and behavioural effects of visual field may not necessarily appear as a consequence of the changing hemispheric influence over time.

#### 8.2.2.2 The dual-route processing in Chinese radical perception

Section 8.2.2.1 just explored how ERP findings in the present thesis provided fresh input to the layer structuring in theoretical models of Chinese character recognition. This section will discuss the implications of findings in the present thesis for understanding the dual route processing in radical and character processing.

As noted in Section 1.2, the pseudoword superiority effect typically observed along with the WSE lends support to the dual-route processing models of word recognition (e.g., Coltheart & Rastle, 1994; Grainger & Jacobs, 1994). Specifically, it is argued that under the lexical route, a learned word is represented as an entry in a mental lexicon which can be directly retrieved from its printed form; under the non-lexical route, however, pronunciation and visual identification of pseudowords can be achieved via readers' reference to a system of spelling and pronunciation rules. With regard to neurophysiological evidence for dual-route processing, no published studies have specifically investigated if the same neural network is responsible for processing words and pseudocharacters in a comprehensive manner by comparing all major ERP components or fMRI ROIs activated by words and pseudowords. Nevertheless, findings in the existing literature show that ERP components (even including the N400 in many studies) and fMRI ROIs activated by word stimuli all responded to pseudowords and these brain responses showed the same hemispheric lateralization to words and pseudowords, as in contrast to visual stimuli of other categories such as faces and

objects.

Results of Experiment 4 in the present thesis show that participants identified radicals with similar level of accuracy when these radicals were embedded in pseudocharacter context or appeared alone. As discussed in Section 6.4, there are two possible explanations for the absence of a behavioural effect of pseudocharacter superiority over single radicals. One possibility is that radical perception can benefit from being in a character-like orthographic context and this orthographic benefit is moderated by the number of radicals contained in the context. Indeed, characters and accordingly pseudocharacters used in the present thesis were all left-right structured with two component radicals whereas observations of English pseudoword superiority reported in the literature have all been obtained with stimuli containing three or more letters, which makes sense as they are, respectively, more representative of the character and the word structure encountered in everyday reading. Indeed, there is evidence showing that the size of the WSE over single letters decreased from 15% for 4-letter words to 10.2% for 3-letter words and to 3.4% for 2-letter words, which is comparable to the size of the character superiority over single radicals found in the present thesis (Samuel et al., 1982). If the absence of the pseudocharacter superiority over single radicals was indeed due to the compositional characteristic of having only two radicals, the implication would be that perceiving a radical together with other radicals when the combination complies with the orthographic rule in Chinese character writing can provide more useful identification clues than perceiving the radical in a non-orthographic context and more importantly this orthographic benefit is modulated by the number of constituent radicals in that orthographic context.

Another possible explanation for the absence of pseudocharacter superiority over single radical conditions could be due to the distinction between the orthographic

validity in Chinese and in English. Specifically, unlike the English language in which orthographic validity relates to the entire letter string, i.e., whether the letter combination abides by English spelling rules, the Chinese language does not have a spelling system and the orthographic validity of a multi-radical structure fully depends on the spatial position of its constituent radicals. In Experiment 4, the target radical in each single-radical stimulus (a semi-inverted character or pseudocharacter) was shown in its regular position as in characters and pseudocharacters. Therefore, the absence of pseudocharacter superiority over single radical conditions might suggest that when a radical outside of a lexical context is shown in its regular position, the neural system can extract this orthographic information equally well no matter whether there is additional orthographic information (e.g., as in the pseudocharacter stimuli) or not (e.g., as in the semi-inverted stimuli) and process the radical on its own based on this information. If this was true, the implication is that the orthographic mechanism proposed for processing English letter strings does not apply to Chinese reading; instead, identification of each individual radical in pseudocharacter or other non-lexical contexts goes through a radical channel and supra-radical information seems to have no impact on single radical processing.

In respect of neurophysiological evidence for possible dual routes in processing multi-radical structures, results of Experiment 5 provided no information as to whether pseudocharacters elicited differential ERPs than single-radical conditions because only characters, pseudocharacters and VMs were used as stimuli. This was due to that the primary aim of the study was to investigate the neural correlates of the character superiority over pseudocharacter and adding single-radical conditions would considerably lengthen the duration of the experiment (already having 1536 trials) and increased participants' feeling of eye strain and fatigue due to the fixation control

procedure. Nevertheless, although it was not possible to determine the exact nature of the non-lexical mechanism involved in pseudocharacter processing, findings of Experiment 5 seem to suggest that this non-lexical processing shares a similar neural network as the lexical processing of characters up until the N400. Specifically, the visuo-perceptual processing of characters and pseudocharacters took place in a coarse-to-fine manner in the occipito-temporal areas (including BA 18, 19), lexical retrieval in centro-frontal areas (BA 9 in particular), and internal stimulus evaluation in occipito-parietal areas, though these areas showed different activation strength and hemispheric lateralization patterns in response to characters and pseudocharacters.

In summary, the absence of pseudocharacter superiority effect over single-radical conditions (and smaller character superiority effect) in the present thesis may have been due to the less compositional complexity of stimuli used here compared to English stimuli which typically contain three or more lower-level components. If this was true, the implication would be that the orthographic benefit to pseudocharacter processing can be modulated by the number of its constituent radicals. Alternatively, the absence of pseudocharacter superiority in the present thesis may suggest that the orthographic mechanism proposed for processing English letter strings does not apply to Chinese reading; instead, identification of each individual radical in pseudocharacter or other non-lexical contexts goes through a radical channel and supra-radical information seems to have no impact on single radical processing. Besides, although it was not possible to determine whether the non-lexical processing of pseudocharacters is purely radical-based or involves supra-radical calculation in the present thesis, findings of Experiment 5 seem to suggest that this non-lexical processing shares a similar neural network as the lexical processing of characters up until the N400.

### 8.3 Future research

The previous sections summarized Chapters 1-7, their findings, how these findings were obtained based on methodological improvements and how they contribute towards the theoretical understanding of Chinese character recognition. There are several ways in which work reported in the present thesis can be improved in future research.

Firstly, experiments reported in the present thesis observed better identification performance for radicals embedded in characters compared to when they were embedded in pseudocharacters or shown as the single radical in a matched visual context. However, the size of this character superiority effect (3-4%) is considerably smaller than the English word superiority (10-15%). Besides, in contrast to the phenomenon that the English WSE is often accompanied by a pseudoword superiority over single letters, there was no pseudocharacter superiority effect observed in the present thesis. Several hypotheses to account for these discrepancies were provided in Section 6.4, including the possibility that the compositional difference in terms of the number of lower-level components may have contributed to the smaller character superiority and the absence of the pseudocharacter superiority. Specifically, characters and accordingly pseudocharacters used in the present thesis were all left-right structured with two constituent radicals whereas the English word and pseudoword superiority effects have typically been obtained with stimuli containing three or more constituent letters. This compositional difference hypothesis needs to be tested in future research to reveal whether the smaller character superiority effect and the absence of the pseudocharacter superiority effect are indeed due to the impact of the number of constituent radicals, just as the English WSE size is modulated by the number of letters, or instead reflect certain language-specific mechanism.

Another important direction of future research is to further test the coarse-to-fine visual processing of Chinese characters and character-like stimuli. Evidence in the literature shows that coarse-to-fine processing seems to be a general visuoperceptual mechanism. Findings of the present thesis that Chinese speakers' visual system responded to characters and their corresponding VMs with similar level of amplitudes while distinguishing both from pseudocharacters early in the P1 suggest that coarse-scale configurational information in characters and character-like stimuli is also processed before the more fine-tuned features are analyzed (mainly in the N1). If it was indeed the shared visual intensity in terms of pixel number and luminance level that had caused similar P1 amplitudes between characters and VMs in the present study, this similarity in the P1 should also be observed between characters and their new visual matches.

ERP comparisons between characters, pseudocharacters and semi-inverted characters will not only provide evidence for or against the proposition of coarse-to-fine visual processing in Chinese characters but also help to determine the nature of the nonlexical radical processing in pseudocharacters. As discussed earlier, if the processing of pseudocharacters benefits from orthographic regularity, ERP differences (especially in the N1) are anticipated between pseudocharacters and semi-inverted characters; otherwise if radicals in nonlexical contexts are processed independently, pseudocharacters and semi-inverted characters should activate similar level of N1 responses.

Last but not least, there are important aspects of the character superiority effect that the present thesis has not touched upon including examining whether manipulating character frequency would result in ERP differences and whether these ERP differences are pre- or post-lexical.

## Appendix 1: Sample stimuli with critical radicals on the left

	Ch pair 1	Ps pair 1	Ch pair 2	Ps pair 2		Ch pair 1	Ps pair 1	Ch pair 2	Ps pair 2
Set 1	清	清	阴	阴	胡	胡	精	精	精
VM	清	清	阴	阴	胡	胡	精	精	精
FI	清	清	阴	阴	胡	胡	精	精	精
SI	清	清	阴	阴	胡	胡	精	精	精
Set 2	梗	梗	惊	惊	梗	梗	梗	梗	梗
VM	梗	梗	惊	惊	梗	梗	梗	梗	梗
FI	梗	梗	惊	惊	梗	梗	梗	梗	梗
SI	梗	梗	惊	惊	梗	梗	梗	梗	梗
Set 3	织	织	狐	狐	织	织	织	织	织
VM	织	织	狐	狐	织	织	织	织	织
FI	织	织	狐	狐	织	织	织	织	织
SI	织	织	狐	狐	织	织	织	织	织
Set 4	杯	杯	拱	拱	杯	杯	杯	杯	杯
VM	杯	杯	拱	拱	杯	杯	杯	杯	杯
FI	杯	杯	拱	拱	杯	杯	杯	杯	杯
SI	杯	杯	拱	拱	杯	杯	杯	杯	杯
Set 5	烘	烘	对	对	烘	烘	烘	烘	烘
VM	烘	烘	对	对	烘	烘	烘	烘	烘
FI	烘	烘	对	对	烘	烘	烘	烘	烘
SI	烘	烘	对	对	烘	烘	烘	烘	烘
Set 6	灯	灯	怕	怕	灯	灯	灯	灯	灯
VM	灯	灯	怕	怕	灯	灯	灯	灯	灯
FI	灯	灯	怕	怕	灯	灯	灯	灯	灯
SI	灯	灯	怕	怕	灯	灯	灯	灯	灯
Set 7	抱	抱	倚	倚	抱	抱	抱	抱	抱
VM	抱	抱	倚	倚	抱	抱	抱	抱	抱
FI	抱	抱	倚	倚	抱	抱	抱	抱	抱
SI	抱	抱	倚	倚	抱	抱	抱	抱	抱
Set 8	晓	晓	福	福	晓	晓	晓	晓	晓
VM	晓	晓	福	福	晓	晓	晓	晓	晓
FI	晓	晓	福	福	晓	晓	晓	晓	晓
SI	晓	晓	福	福	晓	晓	晓	晓	晓
Set 9	掸	掸	框	框	掸	掸	掸	掸	掸
VM	掸	掸	框	框	掸	掸	掸	掸	掸
FI	掸	掸	框	框	掸	掸	掸	掸	掸
SI	掸	掸	框	框	掸	掸	掸	掸	掸
Set 10	调	调	卸	卸	调	调	调	调	调
VM	调	调	卸	卸	调	调	调	调	调
FI	调	调	卸	卸	调	调	调	调	调
SI	调	调	卸	卸	调	调	调	调	调
Set 11	胖	胖	站	站	胖	胖	胖	胖	胖
VM	胖	胖	站	站	胖	胖	胖	胖	胖
FI	胖	胖	站	站	胖	胖	胖	胖	胖
SI	胖	胖	站	站	胖	胖	胖	胖	胖
Set 12	狗	狗	洋	洋	狗	狗	狗	狗	狗
VM	狗	狗	洋	洋	狗	狗	狗	狗	狗
FI	狗	狗	洋	洋	狗	狗	狗	狗	狗
SI	狗	狗	洋	洋	狗	狗	狗	狗	狗

Appendix 1: Sample stimuli with critical radicals on the right

	Ch pair 1	Ps pair 1	Ch pair 2	Ps pair 2
Set 13	列妍	刂妍	玻璃	破璃
VM				
FI				
SI	列妍	刂妍	玻璃	破璃
Set 14	纪纯	纟纯	粘粒	粘粒
VM				
FI				
SI	纪纯	纟纯	粘粒	粘粒
Set 15	冯冰	冫冰	短矩	短矩
VM				
FI				
SI	冯冰	冫冰	短矩	短矩
Set 16	细纱	纟纱	裤裕	裤裕
VM				
FI				
SI	细纱	纟纱	裤裕	裤裕
Set 17	破碗	攴碗	像傀	像傀
VM				
FI				
SI	破碗	攴碗	像傀	像傀
Set 18	扌坊	扌坊	扌拔	扌拔
VM				
FI				
SI	扌坊	扌坊	扌拔	扌拔
Set 19	灶烦	火烦	趾颞	趾颞
VM				
FI				
SI	灶烦	火烦	趾颞	趾颞
Set 20	旋施	辵施	砖研	砖研
VM				
FI				
SI	旋施	辵施	砖研	砖研
Set 21	稀租	禾租	场均	场均
VM				
FI				
SI	稀租	禾租	场均	场均
Set 22	驿骄	辵骄	惧怕	惧怕
VM				
FI				
SI	驿骄	辵骄	惧怕	惧怕
Set 23	祝祠	礻祠	贼贬	贼贬
VM				
FI				
SI	祝祠	礻祠	贼贬	贼贬
Set 24	姑娘	女娘	状妆	状妆
VM				
FI				
SI	姑娘	女娘	状妆	状妆

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