11-16-2022 10:00 AM

The Coding Flexibility of Radical Position in Chinese

Zian Chi, *The University of Western Ontario*

Supervisor: Lupker, Stephen J., *The University of Western Ontario*

A thesis submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree in Psychology

Abstract

Although there are theories of word recognition/reading predicting a transposed letter (TL)-type effect in Chinese character recognition, specifically, a transposed radical (TR) effect, no empirical demonstrations of TR effects have been reported to this point. As a result, instead of adopting a position-general assumption of radical processing, a position-specific assumption of radical processing has been adopted in most Chinese character recognition models. In the present Experiment 1, computational models were created in order to determine whether models that do not make the position-general assumption can account for any TR effect if one were to be found. In Experiment 2, 3, and 4, the masked priming technique was used to investigate whether there are TR priming effects in Chinese character recognition, as well as whether such effects would interact with radical type (character radical vs non-character radical) or character structure (left-right vs top-bottom). Experiment 2 used the lexical decision task (LDT) and Experiment 3 and 4 used the presumably more orthographically oriented same-different matching task (SDMT). Event-related potentials (ERPs) were analysed in Experiment 2 and 3 in order to better examine the time course of any effects. The results of Experiment 1 showed that computational models can produce TL-type effects, but only if trained with orthographic inputs that follow the position-general view of radical processing. Experiments 2 and 3 (using left-right structure characters) showed that TR priming effects do emerge in LDT and SDMT tasks. In the SDMT task, the ERP data showed that the TR effect emerged in a slightly later time window than the repetition priming effect, implying that the TR effect was produced at the orthographic processing stage rather than at an earlier feature processing stage or a later semantic processing stage. In Experiment 4, the TR effect was found to have a different pattern for top-bottom structure characters than for the left-right structure characters of Experiments 2 and 3, indicating an impact of character structure. These results provide support for the position-general view of radical representation, the noisy position coding models of orthographic processing, and the idea that position flexibility of orthographic representations and their processing are shaped by the language environment of the reader.

Keywords

Masked priming, repetition priming, transposition priming, Chinese character, radical, orthographic

Summary for Lay Audience

This dissertation was an examination of the orthographic processing of Chinese radicals, specifically, how readers process radical positions when reading Chinese characters. There are theories that predict that there should be a transposed radical (TR) effect (i.e., if you transpose the two radicals in a character, the recognition system perceives it as being extremely similar to the original character) arising at the orthographic stage of character recognition (i.e., this proposal is referred to as the “position-general” view). However, at present, no empirical demonstrations of TR effects have been reported even though there have been clear demonstrations of transposed character (TC) effects. Most models of Chinese reading, therefore, incorporate the assumption that radical position coding is tied to the radical’s position as it appears in the text being read (i.e., the “position-specific” view). In order to examine this issue more closely and to provide more solid evidence for one or the other of these views, the present experiments were an investigation of whether there actually is a TR effect in Chinese character recognition. In Experiment 1, computational models were built to demonstrate that the position-general view of radicals can predict a TR effect, whereas the position-specific view cannot. In Experiment 2, 3, and 4, various techniques (e.g., the masked priming and the event-related potential techniques) and tasks (i.e., the lexical decision task and the same-different matching task) were used to try to determine whether there actually is a TR effect (arising at the orthographic processing stage of character recognition) and to determine the time course of that potential effect. The results showed that there are TR effects in Chinese character recognition, and that the source of these TR effects is likely the orthographic processing stage, instead of the earlier feature processing stage or the later semantic processing stage. These results provide support for the position-general view of radical representation and for the various theories that predict a TR effect.

Co-Authorship Statement

The data presented in this dissertation were obtained in collaboration with Dr. Stephen J. Lupker, Dr. Xuan Pan (Experiment 2 and 3), and Huilin Chi (Experiment 4). Dr. Stephen Lupker supervised and edited this dissertation.

Acknowledgments

I would first like to thank my supervisor, Dr. Stephen Lupker, for his support, guidance and encouragement through these years in Western. He gave me a lot of freedom in my research and taught me how to make sense of puzzling data and how to design new experiments on the basis of what those data told me. Most importantly, he set the example of a good researcher for me with his rigorous attitude and enthusiasm, traits that always provided a guide for me.

I also would like to thank the members of my advisory committee, Dr. Debra Jared and Dr. Marieke Mur. I have been very lucky to have had you on my committee. Dr. Jared gave me the opportunity to conduct ERP experiments and provided me invaluable advice on my experiments and writings. Dr. Mur gave me a lot of insightful advice on the interpretation of my experimental data, especially the data from the computational simulations.

I am very grateful to my lab mates, Giacomo Spinelli, Huilan Yang, Alex Taikh, Mark McPhedran, and Jason Perry. Thank you for the help in data collection, data analysis, discussion, and for the great time I was able to spend with you all. I also want to thank Toka Zhu, for giving me a lot of advice on both academic and non-academic matters.

My families provided unlimited and invaluable support to me. Without their support it would have been impossible for me to have completed this journey. Thank you to my wife, Xuan Pan, for always being on my side no matter what happened. Thank you to my parents, for selflessly supporting me while I pursued my PhD degree overseas.

Table of Contents

List of Tables

List of Figures

List of Appendices

Chapter 1: Introduction

Successful reading requires the retrieval of both semantic and phonological information based on the orthographic inputs (i.e., words and sentences). Orthographic inputs consist of the glyphs of a writing system (e.g., letters in alphabetic languages) organized in a systematic way. Naturally, forming and building an accurate representation of glyph identities in the orthographic inputs is crucial for successful reading, because words constituted by different sets of glyphs must be quickly and efficiently distinguished. In addition, coding the positions of glyphs in the orthographic input is also critical, because of the existence of anagrams in many languages. Therefore, how glyph position information is represented is one of the most important research topics in the cognitive psychology of reading.

1.1 The Transposed Letter (TL) Effect

In examinations of the accuracy of letter position coding in alphabetic languages, many studies have reported what is referred to as “transposed letter” (TL) effects. In experiments using the unprimed lexical decision task (e.g., Frankish & Turner, 2007; Lee & Taft, 2009), this effect refers to the phenomenon that nonwords created by transposing two internal letters of an existing word (called transposed letter [TL] nonwords, e.g., JUDGE -> jugde) are more likely to be miscategorised as words than nonwords in which those same two letters are replaced (substitution letter [SL] nonwords, e.g., JUDGE -> juqle) and/or are classified as nonwords more slowly than SL nonwords. In experiments using the masked priming paradigm (Forster & Davis, 1984), the TL effect manifests itself as a facilitation effect, a word target is responded to more rapidly when preceded by a briefly presented TL nonword prime than by an SL nonword prime (e.g., Perea & Lupker, 2003; 2004).

These TL effects are incompatible with the various “slot” coding theories of letter position coding (e.g., the Interactive Activation model: McClelland & Rumelhart, 1981, Rumelhart & McClelland, 1982; the Multiple Read-Out model: Grainger & Jacobs, 1996;

the Dual Route Cascaded model: Coltheart et al., 2001; the Bayesian Reader model: Norris, 2006, 2009) according to which letters are rapidly and accurately coded into their positions in the word being read. Some theorists treat these effects as evidence that the positions of the letters in a word are not coded strictly. Several models proposed to explain the TL effects follow this line of logic (e.g., the Spatial Coding model: Davis, 2010; the Overlap model: Gomez et al., 2008; the Noisy Channel Bayesian Reader model: Norris et al., 2010). Although there are important differences in these models, they all assume that there is uncertainty in the early stage of orthographic processing, and it is this uncertainty that causes the TL effect. Thus, these models can be referred to as noisy position coding models.

Another category of models that can explain TL effects but doesn't rely on the assumption of letter position uncertainty assumes that there is an intermediate level of bigram representations between the letter level and the word level representations (e.g., Grainger & van Heuven, 2004; Whitney, 2001). The bigrams are ordinal combinations of adjacent or non-adjacent (up to three letters apart) letters in a word. For example, the word *target* would activate the bigrams *ta*, *tr*, *tg*, *ar*, *ag*, *ae*, *rg*, *re*, *rt*, *ge*, *gt*, and *et*. According to these models, the main reason TL effects emerge is because the sets of bigrams coded when reading a word and when reading its corresponding TL nonword are very similar. This category of models is called Open Bigram models.

Although the early research on TL effects involved English experiments, there are now abundant studies showing that the TL effect is present in other languages. Those languages include Thai (Winskel et al., 2012; Perea et al., 2018), French (Schoonbaert & Grainger, 2004), Spanish (Perea & Lupker, 2004; Perea & Carreiras, 2006), Basque (Duñabeitia et al., 2007), Hindi (Rimzhim, 2020), and Japanese when words are written in Katakana script (Perea & Pérez, 2009; Witzel et al., 2011). In Perea and Pérez's (2009) Experiment 1, for example, a masked priming lexical decision task in Japanese Katakana, which is a syllabic writing system, was used and a significant 19 ms TL priming effect was found. Witzel et al.'s (2011) Experiment 1 also showed a significant 25 ms TL priming effect in a masked priming lexical decision task using Japanese Katakana.

There are, however, also studies showing that the TL effect is absent in certain languages, in particular, Hebrew (Velan & Frost, 2009) and Korean (Lee & Taft, 2009, 2011; Rastle et al., 2019). Hebrew, like Arabic, is one of the Semitic languages which are root-derived. The base of a word, called the root, usually consists of three consonants and conveys the core meaning of the word (Frost, 2012). Using the masked priming paradigm, Velan and Frost (2009) found that when the transposition involved the root letters, TL nonword primes didn't facilitate the recognition of targets if the prime's letters comprised a non-existing root and actually inhibited responding if the transposition comprised an existing root.

Korean uses a writing system called Hangul in which words consists of physically demarcated letter blocks that represent syllables with most syllable blocks involving three letters (e.g., the word 한글 is the Korean spelling of Hangul, which contains two syllables 한 and 글; the first syllable consists of three letters ㅎ, ㅏ, and ㄴ; the second syllable also consists of three letters ㄱ, ㅡ, and ㄹ). Therefore, Korean Hangul is both alphabetic and syllabic. Lee and Taft (2009) examined TL effects in Korean Hangul using a lexical decision task, and only found a significant TL effect in the by-subject analysis for one (coda-coda) out of three types of cross syllable transpositions (onset-onset, coda-coda and coda-onset). Two types of within syllable transpositions (onset-coda and coda-coda) were further investigated by Lee and Taft (2011) and no TL effect was found in that situation either. Rastle et al. (2019) carried out 5 masked priming experiments to compare TL effects in Korean Hangul and English. They didn't find a Korean TL effect when using onset-coda transpositions in monosyllabic words (in their Experiment 1), when using within syllable onset-coda transpositions in either the first or second syllable of disyllabic words (Experiment 3), or when using coda-onset transpositions involving letters in the first and second syllables (Experiment 5).

The Korean language and the Hangul writing system it uses is certainly very different from the Indo-European languages, while the Hebrew language and its alphabetic system is more similar to the Indo-European languages. But despite their apparent differences and despite the similarity between Hebrew and Indo-European languages, Korean and Hebrew are similar in that neither shows a TL effect. The fact that the TL effect has been found in many languages indicates that the existence of an orthographic process that generates letter/component position flexibility is not restricted to English or to Indo-European languages. However, the absence of TL effect in some languages is a result that needs additional attention because it seems to imply that a high level of flexibility in position coding is not a ubiquitous feature of the reading system in all languages. Instead, it suggests that certain unique orthographic properties of a language can impose constraints on the flexibility of position coding of letters/components when reading in some languages.

Trying to explain this cross-language difference, Frost (2012) argued that the language's orthographic density can be a constraint on the flexibility of position coding. Frost's argument is that reading is a learned skill, so it should be dependent on and shaped by the statistical properties of the language and its writing system. Because in languages like English, where anagrams are somewhat rare (although anagrams are relatively common in three- or four-letter English words, words of those lengths comprise only 1.5% and 5.7% of the words in the language, respectively, according to Shillcock et al., 2000), accurately coding and determining the position of letters is not a crucial requirement for completing the task of retrieving the semantic and phonological information from orthographic inputs. However, in orthographically dense Hebrew there are many anagrams. Therefore, the system "learns" to prioritize the process of coding letter positions.

The same reasoning could also apply to Korean Hangul because its rigid internal structure of syllables and limited number of vowels and consonants makes it an orthographically dense script. "Of the 2,066 syllable blocks … 32% are onset-coda anagrams of another syllable block" (Rastle et al., 2019, p. 459). Interestingly, one unique feature of Korean Hangul, that syllables of the word are demarcated by a physical gap and each syllable itself is arranged in a top-to-bottom fashion, sets it apart from

Hebrew. This visuospatial feature makes it difficult to completely attribute the lack of TL priming in Korean to its dense orthography. Lee and Taft (2009, 2011) suggested that this special feature can help prevent confusion when Hangul letters are placed in an incorrect position/slot (i.e., leading to a reduced or null TL effect). This speculation is relevant here because in Chinese, the language used in the present experiment, there are different kinds of character structures. The most common one is the left-right structure in which the radicals are organized from left to right, the direction of reading. The second most common structure is the top-bottom structure in which the radicals are organized from top to bottom, which is perpendicular to the reading direction. This top-bottom structure resembles the special visuospatial feature of Hangul syllables and a possible implication is that character structure could have an impact on the orthographic processing in character recognition in Chinese.

Support for Frost's (2012) basic argument comes from several studies. Velan and Frost (2011) found that the morphologically simple words in Hebrew (non-root-derived words) did show typical TL effects. Using Arabic, which, like Hebrew, is a Semitic language, Perea et al. (2010) reported that a reliable TL priming effect can be found when the ordering of the letters of the root is kept intact (i.e., when the transposition involves non-root letters). In their Experiment 2, Rastle et al. (2019) found that the lexical decision latency to three-letter monosyllable English target words was not affected by the presentation of a TL prime. These results suggest that the system responsible for reading can pick up the statistical properties of a language environment when learning to read and can then adapt to those properties. As a result, the system will put more focus on letter position information when it learns to read in an orthographically dense language and less focus when learning to read in an orthographically sparse language.

Using a novel paradigm involving teaching participants to read in artificial scripts, Lally et al. (2020) provided further support for Frost's (2012) hypothesis. Lally et al. (2020) created two artificial scripts that were matched on overall frequency and positional frequency of individual symbols, but critically differed in the number of anagrams. One script was sparse (i.e., having no anagrams) and the other one was dense (all words having anagrams). Groups of participants were taught how to read words in one or the other of the novel scripts for four days. On the fifth day, they were tested with a reading out loud task, an orthographic search task, a visual lexical decision task, and a generalisation task (reading a set of untrained novel words aloud). Lally et al. found that, in the visual lexical decision task, the participants in the sparse group showed a larger TL effect than those in the dense group.

Another study supporting these ideas involved computer simulations which showed that distributed-connectionist networks yield more flexible position coding when trained on sparse orthographies compared to dense orthographies (Lerner et al., 2014). These studies all support the argument made by Frost (2012) that the position flexibility of orthographic representations is shaped by the statistical structure of the writing system being learned.

1.2 Is There TL-Type Effect in Chinese?

The main goal of the present research is to investigate the extent to which a certain type of transposition effect exists in Chinese character recognition. The logographic Chinese language is unlike the languages/scripts used in previous TL investigations in that it doesn't use a small number of alphabetic or syllabic symbols and doesn't have grapheme-to-phoneme rules. Instead, Chinese uses a writing script composed of a large number of different characters, most of which consist of two or more radicals[1]. The study of TL type effects in Chinese can, therefore, provide unique information about how our cognitive system handles transpositions of orthographic information, hence, contributing to the mission of finding a more general model of visual word recognition.

---

[1] The term *radical* is often used as a synonym for *component* in the literature, but the two terms do not actually mean the same thing. A *component* is a pattern of strokes that partially forms a compound character. The *radicals* in Chinese are a special group of components traditionally used as indices to categorize all the characters in a dictionary (i.e., *radicals* are a subset of *components*). Many studies used the word *radical*, but what was actually investigated was *components*. However, in order to maintain consistency with previous studies, the term *radical* will be used to refer to components in the present manuscript.

As noted, the goal of reading is activating semantic and phonological information from printed words. Achieving this goal is one function of our cognitive system and must, of course, be addressed within the specific language environment of the individual reader. As shown by the studies of the TL effect, that effect is a benchmark of the reading system in Indo-European languages but is missing in Hebrew and Korean. The implication is that the expression of the TL effect is modulated by the specific language environment. Therefore, before forming a hypothesis of any potential TL type effects in Chinese character recognition, we need to look closely at the details of the Chinese writing system and the radicals which are used to form characters.

1.2.1 The Chinese writing system

Like English, the orthographic system of Chinese can be described at several different levels: strokes, radicals, characters, and words. Therefore, the relevant levels, from high to low are: words which consist of one or more characters that have individual meanings; characters which involve one or more radicals which can provide both semantic and phonological information about the word; radicals which are constructed by a combination of stroke patterns and usually occupy a rectangle-shaped space; strokes which are line patterns that can be arranged to form a radical and/or a character. More concretely, consider the word 纷飞 (which means flurry in English): The word consists of two characters, 纷 and 飞. The first character 纷 can be decomposed into the radicals 纟 and 分, but the second character 飞 cannot be decomposed. Focusing on the level of words, previous studies have found the so-called transposed character (TC) effects using multiple character words. For example, Gu and Li (2015) used the eye movement technique and boundary paradigm and found that, for four-character words, the gaze duration on the substitute character (SC) condition (in which nonwords were created by substituting the middle two characters) was longer than the TC condition (in which nonwords were created by transposing the middle two characters). Also using four-character words, Yang et al.'s (2019) Experiment 1 demonstrated that a TC priming effect, which is analogous to a TL priming effect, can be found in Chinese, indicating that the orthographic processing of Chinese words can tolerate the ambiguity of positions of characters to at least some degree. Yang et al. (2020) further demonstrated that the locus of this effect is almost certainly the orthographic coding process.

As mentioned above, however, there is a lower level of orthography than characters in Chinese, namely the level of radicals. In Chinese, nearly 80% of all characters are formed by two or more radicals (Xing, 2007). Some radicals can only legally exist in a particular position when in a character (e.g., 纟 only occurs on the left-hand side of a character). Radicals of this kind are referred as bound radicals. Other radicals can legally exist in more than one position in a character (e.g., 分 can legally stand on the left-hand side as in a character such as in 颁, or on the right-hand side as in a character such as in 纷). Radicals of this kind are referred as free radicals. Many radicals are characters themselves (and can't be decomposed further) and have their own meanings. They are often called character radicals (CRs). The radicals that can't stand alone as characters are called the non-character radicals (NCRs).

Radicals can also be divided into semantic and phonetic radicals. They can provide some amount of semantic and phonological information, respectively, about the character containing them. If a compound character contains a phonetic radical and has the same pronunciation as its phonetic radical, then it is called regular. If it does not have the same pronunciation, then it is called irregular.

With regard to the way of arrangement of different radicals that form a character, the Unicode Standard (The Unicode Consortium, 2020) summarised 12 structures to explain how to describe and analyse a character. Among the 12 structures, the left-right structure and the top-bottom structure are most common. For example, the two-radical character 纷 has a left-right structure, in which one radical is on the left side and the other one is on the right side. The character 芬 has a top-bottom structure in which the two radicals are on the top and bottom respectively.

The 6500 level one and level two characters (i.e., the common characters) of the *Table of General Standard Chinese Characters* (Ministry of Education of the People's Republic of

China, 2013) can be decomposed into more than 1600 different radicals. Among these 6500 characters, only 85 (1.3%) have counterpart character(s) that involve the same radicals (i.e., only 85 characters are radical anagrams). This fact, based on Frost's (2012) analysis, would seem to suggest that if radicals are identified during reading, character recognition should follow directly even if position information is not readily established. Therefore, the recognition system should not be tuned to demand precise radical position information.

1.3 Two Views of the Orthographic Coding of Radical Positions

Studies investigating the properties of radicals have found that radicals, as subcharacter components, do get activated and affect the orthographic processing of Chinese characters (Taft & Zhu, 1997; Zhou & Marslen-Wilson, 1999; Ding et al., 2004; Chen & Yeh, 2015). For example, Zhou and Marslen-Wilson (1999) found a priming effect in a naming task when the prime character is semantically related to one radical of the target character. This effect suggests that when reading in Chinese, the recognition system doesn't treat each character as a whole, but rather, in some way, decomposes it into its components (i.e., radicals). Another example is the regularity effect of Chinese character recognition, the phenomenon that the naming of regular characters is faster than that of the irregular characters (e.g., Plaut et al., 1996; Lee, 2008). Hence, the question of whether the orthographic coding of radical position is flexible (like the case for English) or rigid (like the case for Hebrew and Korean Hangul) becomes an important one.

With respect to this question, previous studies have shown mixed results, leading to the generation of two different views. One view is called the position-specific view of radical representation, according to which radicals are inevitably coded into their correct position (e.g., Taft et al., 1999; Ding et al., 2004; Taft, 2006). Note that this view is not consistent with Frost's (2012) hypothesis given the nature of the structure of Chinese characters (i.e., few characters contain the same set of radicals), nor is it consistent with the noisy position coding models since these models assume noise in the early orthographic processing stage which should be a universal phenomenon and, hence, applicable to

Chinese characters. The other view of radical position representation can be called the position-general view (e.g., Tsang & Chen, 2009), a view that would be consistent with both Frost's (2012) hypothesis and the noisy position coding models.

1.3.1 The position-specific view

The position-specific view holds that the mental representations of radicals contain position information. Hence, there are two ways in which free radicals like 分 are represented when reading. Essentially, only the one appropriate to the position of the radical in the character being read is activated and that radical input stimulates and activates only the representations of characters having that radical in the same position. This view resembles the assumption in the early "slot-coding" models of word recognition in alphabetic languages, for example, the Interactive-Activation (IA) model in which an activated letter node only sends activation to word nodes that contain that letter in the same position. Similarly, the Implemented Lexical Constituency Model (Perfetti et al., 2005) also assumes that a perceived radical can send activation only to character representations that contain that radical in the same position. In fact, Perfetti et al. ran a computer simulation based on that assumption, though with a limited set of characters and with a goal other than testing their positional orthographic coding assumption, and generated results showing a pattern similar to that in the behavioural data in one of their earlier studies (Perfetti & Tan, 1998).

Taft and Zhu (1997) proposed what has become possibly the most impactful model of Chinese reading, the Multilevel Interactive-Activation framework, which was expanded and elaborated in Taft (2006). This model makes the explicit assumption that the activation of the representation of a compound character is mediated by position-specific radical units. This model also directly assumes that radicals in different positions evoke different representations. For example, in the recognition of characters which contain the radical 分, like 纷 and 颁, the general representation of 分 would be activated and combined with a tag indicating its position. Then the position-specific representations right-分 and left-分 would get activated respectively, mediating the activation of the representations of characters that only contain the radical on the same position. Importantly, the model also postulates that “there is an inhibition device existing within the character-recognition mechanism (with inhibitory links between either the character units or the radical units) that is activated via shared features” (Ding et al., 2004). In other words, it assumes that there exists an inhibition between different position-specific units for the same radical (e.g., the activation of left-分 inhibits the activation of right-分, and vice versa). Based on these assumptions, it can be predicted that: (1) If we use a left-分 character to prime the target 纷 in a masked priming experiment, there will be no priming effect; (2) Similarly, if we use a left-分 and right-纟 to prime the target character 纷, which contains a right-分 and left-纟, there should also be no priming effect, and, in both cases, there may even be an inhibition effect.

Studies of Chinese character recognition using computational modeling have mostly adopted this position-specific view of radical representation, implicitly or explicitly. For instance, Chang et al. (2016) in their investigation of the inhibitory effect of neighborhood size in Chinese used a computational model of Chinese character naming based on the position-specific assumption. They used bitmap images as orthographic input for their model. The stimuli were explicitly created in a way that each character consisted of two radical bitmaps in which the left radical was always in the left bitmap and the right radical was in the right bitmap. Therefore, a radical in two different positions would have two different representations according to their model and those representations are responsible for separately activating the characters containing the radical in those positions. Yang et al. (2009) and Yang et al. (2013) proposed a similar model which was based on distributed orthographic representations of radicals. They included nodes to code the structures of characters with the radicals in a character always being coded from left to right or from top to bottom. This type of model is, of course, also based on the implicit assumption that a radical in different positions would be coded differently.

In fact, there appears to be ample empirical evidence supporting the position-specific view of Chinese radical representation. Taft et al. (1999), for example, tested this hypothesis using the few Chinese characters whose two radicals can be transposed to create a different character in a lexical decision task. The logic is that, if the representations of radicals are position-specific, then the latency to those radical-transposable characters (they would be analogous to English words like CALM, which is CLAM if we transpose its middle two letters) should not be different from the latency to radical-not-transposable characters which would be non-characters if their radicals were transposed (they would be analogous to English words like CLUE, which is not a word if we transpose the middle two letters). Indeed, in English, transposable words like CALM are responded to slower than non-transposable words like CLUE (Andrews, 1996). In Taft et al.'s lexical decision task, participants did not response to the transposable characters (e.g., 杏 and 呆) slower than to control characters, suggesting that these characters were not perceived as being particularly similar.

Ding et al.'s (2004) Experiment 3 also provided supporting evidence for the position-specific radical assumption as they obtained a masked priming effect in a lexical decision task only when the prime character had a shared radical in the same position as in the target character. When the shared radical was in a different position, the priming effect was not significant. Further, Su et al. (2012), using a masked priming lexical decision task, found a greater effect in Event-Related Potentials (ERPs) for the characters with radicals in their more typical positions than in their less typical positions. Finally, Chen and Yeh (2017) examined the repetition blindness effect using Chinese characters in a rapid serial visual presentation (RSVP) paradigm. In their Experiment 1A, they manipulated the radical position and found that participants made significantly more mistakes in reporting the characters in an RSVP stream (i.e., the typical repetition blindness effect pattern) when the characters had the same radical in the same position than when they had the radical in a different position.

1.3.2 The position-general view

What’s important to note is that there are also data supporting the position-general view of radical representation, that is, the view that the orthographic coding of Chinese radicals is position general. Directly testing the impact of radical position on Chinese character processing, Tsang and Chen (2009) used a character matching task in which participants decided whether a target character had been displayed after two briefly and sequentially presented source characters. They found that regardless of whether the position of the shared radical was the same or not, the participants took longer and made more mistakes in rejecting a target character which was different from the source characters but shared a radical with them (in comparison to a control target). In other words, a single radical shared between the target character and the source characters, regardless of the radical’s position, was sufficient to generate an illusory perceptual effect. This result supports the position-general view of Chinese radical representations.

In another example, Wang et al. (2022) used the picture-word interference paradigm, which required the participants to write down the correct character when they see a target picture (i.e., the picture’s name) while ignoring a distractor character on the picture, in order to examine the role of radical position in character production. They reported that radicals embedded in the same character structure as the target’s name significantly shortened the participants’ responding latency, no matter whether the radicals appeared in the same or in a different position in the distractor.

It has also been noted that there were two potential problems in previous studies reporting results supporting the position-specific view. First, different character structures were mixed in the stimuli used. Unlike English, which is written in a linear style, Chinese characters, as noted, can be constructed in different ways (e.g., vertically or horizontally constructed resulting in the top-bottom or left-right structures) and there is no evidence that characters with different structures are orthographically processed in the same way. As mentioned earlier, the special visuospatial configuration of Korean Hangul might be at least partially responsible for the lack of a TL effect in Korean (Lee & Taft, 2009, 2011), and it is possible that a rarer structure in Chinese, the top-bottom structure, could have a similar impact.

Indeed, there is evidence that the character structure does have an impact on the perception of character similarity (Yeh & Li, 2002) and affects the nature of effects in character naming (e.g., the regularity effect, Cai et al., 2012). Results such as these certainly provide a warning that mixing different character structures in the materials could potentially affect the results. Nonetheless, in some of the studies that obtained results supporting the position-specific view, the researchers didn't take structure into consideration and used compound characters with different structures without implementing the necessary counterbalancing procedures (e.g., Taft et al., 1999; Su et al., 2012). Although the question of whether structure affects the orthographic processing of characters has yet to be resolved, it is certainly not guaranteed that it would be safe to use different character structures in the targets without applying some sort of counterbalancing procedure.

There is also evidence that the character structure affects the character production procedure. For example, using the picture-word interference paradigm Wang et al. (2022) found that when the shared radical appeared in the distractor that possessed a different structure than the target (e.g., top-bottom rather than left-right), only a non-significant facilitation trend was observed. This result indicated there is an impact of structure in the character production procedure.

A second potential problem with a number of the studies supporting the position-specific view is that they used characters involving the same radical on different sides without taking into consideration of how doing so changes the look of the radical. In Chinese script, the same radical in different positions usually has different sizes (e.g., the size is usually larger when a radical is on the right than left side), and sometimes it may even have different shapes. For instance, 纷 and 颁 have the same radical 分 on different sides, and the radical is larger in the former character than in the latter character. 恍 and 辉 have the same radical 光, but the radical has different sizes and different shapes when it is on different sides. This situation can introduce a confound that may have benefitted the processing of a radical in the same position condition in previous studies. For example, Ding et al.'s (2004) Experiment 3 used character pairs that have same radical in the same or different positions in the prime and target. They found a significant 23 ms masked priming facilitation effect compared to an unrelated condition when the radical was in the same position in the prime and target (e.g., 躯-枢), but when the same radical was in different positions in the prime and target (e.g., 欧-枢) there was only a nonsignificant 11 ms facilitation effect. This data pattern could have been a result of the aforementioned confound. One way to avoid this problem is to create the TR non-characters while maintaining the sizes and shapes of the radicals when they are transposed. This practice was applied in the present Experiments 2, 3 and 4 when creating transposed radical (TR) primes.

What's also worth noting is that most data supporting the position-specific assumption come from experiments involving clear presentations of the critical stimuli. Because the orthographic processing stage for radical positions should be early and could be vague and inaccurate, but ultimately the positions of radicals should be resolved clearly after a certain amount of time of exposure to the character in successful reading, the paradigms using clear presentations of critical stimuli are likely easily affected by post-orthographic coding effects. In addition, these types of paradigms are also susceptible to participants' strategic processing. Thus, investigations of the existence of a TR effect using subliminal presentations of stimuli (e.g., using the masked priming technique) would seem to provide a less contaminated view of this issue because those types of experimental paradigms would be less subject to the impact of later processes. Of course, there are studies supporting the position-specific assumption that didn't only involve clear presentation of stimuli (e.g., Ding et al., 2004; Chen & Yeh, 2017), but those studies involved the second potential problem discussed above (i.e., size and shape differences). Indeed, as mentioned above, Ding et al. (2004) did find a 11 ms facilitation effect in the different position condition, which would be consistent with the idea that when using subliminal presentations of stimuli, a TR effect would be easier to observe because the post-orthographic effects would be less dominant.

1.4 The Present Research

According to Frost's (2012) analysis and the noisy position coding models, the Chinese language should allow for a certain amount of position flexibility in the coding of radicals in character recognition. Therefore, one would expect that there would be a TR effect in Chinese character recognition. Moreover, by resolving this question, while addressing the potential problems in previous studies, we should have an answer as to whether the position-specific view or the position-general view of radical position coding is correct. The present experiments were focused on within character transposition because the previous studies investigating radical position coding mostly used single characters as stimuli. The principles of Frost's (2012) analysis and the noisy position coding models should apply similarly to TR in a single character and TR in a multiple character word. The main goal of Experiment 1 was to determine whether the position-specific assumption could predict a TR effect and to verify that the position-general assumption can do so using computer simulations. The goal of Experiments 2 to 4 is to directly investigate whether a TR priming effect exists, and if so, if it is altered by task type (masked priming lexical decision task versus a masked priming same-different task), radical type (CR or NCR) or character structure.

The radical type (CR or NCR) is a factor that, like the character structure, has been both less investigated and less controlled for in previous studies investigating the position-specific account of radical processing. Since a CR is a character by itself, unlike an NCR, which can only exist in a character in combination with another radical, it's reasonable to suspect that position information is more important for an NCR than for a CR. Therefore, if any TR effect is affected by the radical type, it's expected that the characters containing only CRs will show larger TR effects than the characters containing NCRs.

In Experiment 1, computational models were created in order to determine whether models that do not make the position-general assumption can account for TR effects. If TR effects are observed in subsequent experiments, such a result would, indeed, provide good support for the position-general assumption.

In Experiment 2, the lexical decision task was used in order to test whether a TR masked priming effect would appear. In Experiment 3, the masked priming same-different matching task, a task more directly tapping into early, orthographically based processing, was used. The reason for using the same-different matching task is that it is well known that many factors other than orthography can affect the performance in a lexical decision task. Therefore, it can be difficult to distinguish higher-level effects from lower-level orthographic effects in this task. On the other hand, in the masked priming same-different matching task, it seems to be the case that other factors, for example, semantic and lexical factors (e.g., frequency) play, at most, a very minor role.

Whereas the response latencies in behavioural data only denote the final point of all the cognitive processing events in reading, ERP data can provide information about the temporal sequence of these events. Therefore, in Experiment 2 and 3, in addition to the response latency data, electroencephalography (EEG) data were also collected in order to better investigate the origin of any TR effect and to compare the different effects of the two paradigms.

In Experiment 4, characters with a different structure, the top-bottom structure, were used as stimuli in order to examine whether the pattern of TR priming effects observed for the left-right structure characters also emerges for characters with a top-bottom structure. The task was the same as Experiment 3 (i.e., the masked priming same-different matching task) since that task is more orthographically based. If a TR priming effect only manifests itself in the left-right structure characters and not the top-bottom structure characters, this pattern would indicate that the confound of using different structure characters in previous experiments may have contributed to the absence of effects and, hence, those experiments' support for the position-specific view. If a TR priming effect can be found in both top-bottom and left-right structure characters, this pattern would indicate that the position coding of radicals is position general regardless of the character structure. The existence of a TR effect would also have important implication for building computational models of Chinese reading.

Chapter 2: Experiments

2.1 Experiment 1

At this point, there is very little evidence of TR effects, causing theories of Chinese word recognition and studies of Chinese character recognition using computational modeling methods to adopt the position-specific view of radical representation (e.g., Taft, 2006; Xing et al., 2004; Yang et al., 2009, 2013). However, there are data (e.g., Tsang & Chen, 2009) supporting the position-general view of radical representation. Also, most data supporting the position-specific assumption come from experiments involving clear presentations of the stimuli which would give post-orthographic coding effects much more opportunity to show up. Further, the structure and shape change of radicals in the character materials have often been neglected in the previous studies supporting the position-specific assumption. All of these issues make the support for the position-specific assumption less solid than it may appear.

Before pursuing these issues, it seemed to be necessary to determine whether the position-sensitive and/or position-general assumption of radical position representation can produce TR like behaviour in models trained to learn the print-to-sound associations of Chinese characters. The expectation is that models based on the former assumption will fail whereas models based on the latter assumption will succeed. Further, by lowering the weight of the position information in the orthographic coding process, we can mimic the property of our visual system that position information is processed with less precision than identity information and test whether this property would be responsible for creating a TR effect.

2.1.1 Method

Model. The model architectures were inspired by the model architectures used in simulation 1 and 2 in Lerner et al. (2014). Unlike mapping orthographic input representations to artificial semantic representations which were generated randomly in Lerner et al. (2014), the models in this experiment map orthographic input representations to phonological output representations which were generated on the basis of the actual pronunciation of the characters[2]. Three models were built and trained. In all three models, the input representations went through the first (with 2000 nodes) and the second hidden layer (also with 2000 nodes) before they ultimately fed into a 61-node phonological output layer. The number of nodes in the hidden layer 1 was larger than that in simulation 1 of Lerner et al. (2014) which used 400 nodes. Although the increased number of nodes was driven by the fact that orthographic inputs were longer than those used in the simulations of Lerner et al. (2014), the number of nodes selected (2000) was arbitrary. If the number of nodes in the hidden layer is too small, the networks may fail to reach a high accuracy in the task. Therefore, the hidden layer node sizes needed to be reasonably large (e.g., 2000), in order for the learning to ultimately be successful. However, because the goal of the present experiment was not to find the most economic size of hidden layers used in building neural networks that are acceptably good at generating phonological outputs from orthographic inputs, the hidden layer node sizes were not used as hyper parameters and examined when building the networks.

[2] In Lerner et al. (2014) they used artificial semantic output representations to reflect the arbitrary nature of orthographic-to-semantic coding. Instead of following this approach, I created phonological output representations based on the real pronunciations of the characters. The phonological output representations can serve the goal allowing me to determine whether the models successfully learned the correct correspondence. Note also that the key difference between M1 and M2/M3 was in the orthographic input representations, with the phonological output representation being the same for all three models. Therefore, any performance difference in the models should be attributable mainly to the differences in the orthographic inputs.

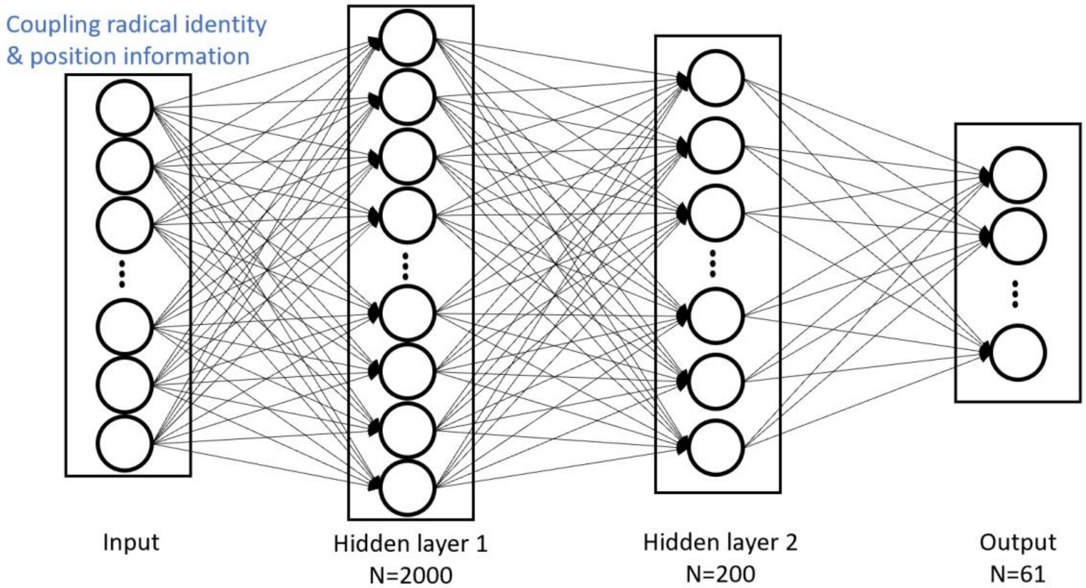

Figure 1: Model architecture used for M1.

The first model (M1) was trained with orthographic input representations that have coupled identity and position information. The nodes in the input layer were fully connected to the nodes in the first hidden layer. The second and third models (M2 and M3) were trained with orthographic input representations that have separate identity and position information. The identity and position information were separately pre-processed in half of the first hidden layer and then combined and processed in the second hidden layer.

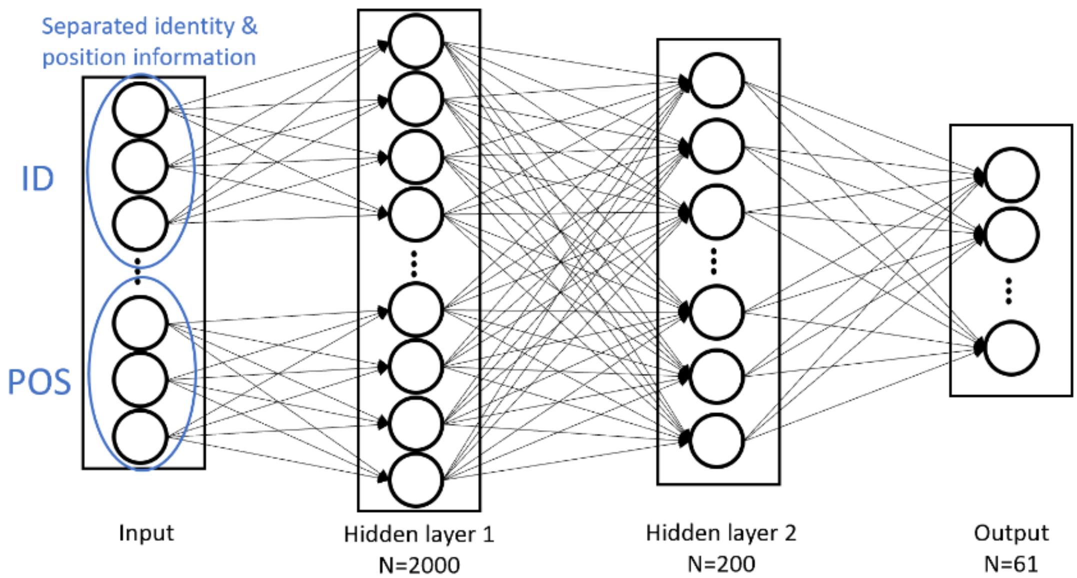

Figure 2: Model architecture used for M2.

In these simulations, the net input of each unit in a layer in the network was the sum of the activity of the units connected to it in the previous layer, as well as that of a bias connection, multiplied by the connection weights between these units. A unit's output was a sigmoidal function of its net input.

Materials. The orthographic and phonological representations were generated for 5209 level one and two characters (i.e., common characters) from the *Table of General Standard Chinese Characters* (Ministry of Education of the People's Republic of China, 2013) that have larger than zero frequency per million characters (i.e., CHR/Million > 0) according to the SUBTLEX-CH database (Cai & Brysbaert, 2010). The phonological representations were 61-bit binary numbers in which 23 bits were used to encode the initial pinyin[3] of the character, 33 bits were used to encode the final pinyin and 5 bits were to encode the tone of the characters.

---

[3] Pinyin or Hanyu Pinyin is the official Romanization system for Chinese Mandarin. It uses Latin letters or clusters of Latin letters to denote initials and finals. The initials are initial consonants (similar to onsets),

According to the position-specific assumption: (1) the identity and position information of radicals are coupled together; (2) the same radical has completely different orthographic codings when it is on different sides of a character. Therefore, the orthographic input representations for M1 were created with an encoding method that coupled identity and position information. Each character was first decomposed into structures and radical sequences using an IDS (ideographic description sequence) table (https://github.com/cjkvi/cjkvi-ids). Since the most complex characters in the material had 6 radicals and there were 1621 different radicals involving 12 different structures in total, 4 bits were used to encode character structure and 66 bits were used to encode the radical sequence (11 bits for each radical in the sequence) for each character.

The orthographic input representations for M2 and M3 were created with an encoding method that has separate identity and position information. A 1659-bit binary number was used to encode each character. Among the 1659 bits, 1621 were used to encode the character's radical identity information, 36 bits were used for the radical position information and 4 bits were used to represent the structure. For the radical identity, each bit of the 1621 bits corresponded to a radical and was assigned 1 if the radical is present in the character, otherwise 0. The 36 radical position bits were made up of six slots each of which had 6 bits. Each slot corresponded to a radical that was present in the character. Each bit in a slot corresponded to a position, and was assigned the value 1 if the radical of the slot was in that position. Using the English word CAT as an example, since there are 26 letters in English, the identity code would be "10100000000000000001000000" because the first, third and twentieth letters of the 26 letters (in the alphabetical order) are present in CAT. The position code would be "010000000000000 100000000000000 001000000000000 000000000000000 …" because the first letter identified as being in the word (the letter A) is the second letter in the word, and the second identified letter (C) is the first letter in the word, and the third identified letter (T) is in the third position. In

---

and the finals are the combination of medials, nucleus and coda. Diacritics are used to denote different tones.

this way of coding, the identity and information are not coupled together, and anagrams would have very similar orthographic representations (differing by only a few bits). For M3, the position representations were scaled down by multiplying the representation by 0.2.

The materials used in testing the models after learning was complete which does so in a way that simulates masked priming effects were TR and unrelated non-characters created based on characters from the training set that contain two or more radicals (5063 of them). The TR materials were created by transposing the first two radicals. The unrelated materials were created by transposing the two radicals from another unrelated character in a way that doesn't create a legal character. Both the TR and unrelated materials were processed with the same orthographic encoding as the materials used for training M1, M2 and M3.

Procedure. *Training*. All weights in the network were initialized to small random values drawn from a uniform distribution, range [-0.01, 0.01]. The models were trained by presenting each input and allowing activation to feed forward to activate a phonological output. That output was then compared to the target output for that word and error was calculated using cross entropy (Hinton, 1989)[4]. Error was accumulated across all of the characters in the training corpus and weights were adjusted based on the accumulated error after a full sweep through the training material. Weight adjustments were based on the delta-bar-delta variation of the back-propagation algorithm (Jacobs, 1988; Rumelhart et al., 1986), using a global learning rate of 0.0001, a momentum of 0.9 and a decay of 0.00001. The local learning rate for each weight was initialized to 1.0 and adjusted over training with an additive increment of 0.1 and a multiplication decrement of 0.9 (see

---

[4] Typically, the cross entropy is used for calculating loss in one-hot outputs. However, one can use cross entropy for a multi-label problem simply by calculating the cross entropy loss across all output classes. Specifically in Experiment 1, since the sigmoid function was used in the output layer and the output representation was not a one-hot vector, the binary cross entropy could be calculated for each character and then those values could be summed up to get the total loss.

Plaut, 1997). The training of a model stopped when "a homeostatic stopping criterion was reached, wherein the effects of weight decay were effectively cancelling out the effects of error-driven learning" (Lerner et al., 2014). Specifically, training stopped when the following two criteria were met: (1) More than 99.95% of the characters' orthographic input activated an output in which each unit was within +/-0.5 of its target value. Fulfilling these criteria means that the phonological outputs generated by the model were most similar to the correct output than to outputs for other characters in the training material for the vast majority of the characters. (2) The average error reduction between two successive batches of 100 sweeps of the inputs was less than 5%.

Testing. After a model had been trained, inputs generated from TR and unrelated testing materials (TR_x and unre_x), as well as the corresponding original materials (base_x), were fed into the model to generate phonological representation outputs (TR_y, unre_y, and base_y). The simulated TR effect of a model was calculated in the following way. First, the correlation scores between base_y and both TR_y and unre_y were calculated. Next, the correlation between unre_y and base_y was subtracted from the correlation between TR_y and base_y. As the unrelated non-characters are completely different from the base characters, it was expected that the correlations between unre_y and base_y would be small. If the model was good at differentiating the TR non-characters from their base characters, the correlation between TR_y and base_y would also be small and quite similar to the correlation between the unre_y and base_y. Subtracting the latter correlation from the former would produce a small difference indicative of a small masked priming effect. If the model was poor at differentiating the TR non-characters from their base characters, it would generate outputs that lead to a high correlation between TR_y and base_y. Subtracting the correlation between unre_y and base_y from that value would then yield a large difference which would imply a large masked priming effect. Using this procedure, the difference between correlations can be taken to reflect the degree of facilitation that the TR non-character would produce as a prime for the base character.

2.1.2 Results

All three models reached the stop criteria in the training phase. It took 46801, 33959, and 72433 sweeps respectively for M1, M2 and M3 to reach the stop criteria of learning. Then the weights of the models were frozen, and the testing materials were fed to the models to get the average correlation scores and to calculate the simulated TR effects. The correlation scores between the phonological representations activated by the orthographic representations of the base characters and those activated by the orthographic representations of the TR and unrelated non-characters are 0.113 and 0.095 respectively for M1, 0.933 and 0.087 for M2, and 0.986 and 0.087 for M3. The simulated TR effects are, therefore, 0.017, 0.847 and 0.899 for M1, M2 and M3 respectively.

I also tested the simulated TR effects for two-radical characters of the most common two structures, the left-right structure (3185 of them) and the top-bottom structure (1121 of them). For the left-right structure characters, the correlation scores are 0.109 and 0.092 for M1, 0.939 and 0.082 for M2, and 0.986 and 0.082 for M3. The simulated TR effects are, therefore, 0.016 for M1, 0.857 for M2, and 0.904 for M3. For the top-bottom structure characters, the correlation scores are 0.121 and 0.085 for M1, 0.927 and 0.083 for M2, and 0.981 and 0.082 for M3. The simulated TR effects are, therefore, 0.037 for M1, 0.844 for M2, and 0.899 for M3.

2.1.3 Discussion

According to Frost (2012), whether there is a TL type effect in a language depends on the language environment provided by the language's written system. A TL type effect is not solely caused by certain properties of the reader's recognition system, such as a noise in orthographic coding or a bigram intermediate level. Rather, Frost argued that a TL type effect is the result of some constraints the language environment puts on the reading system and that the orthographic depth of the language is one such constraint. The Chinese writing script is very sparse orthographically, because only 1.3% of the 6500 common characters in the *Table of General Standard Chinese Characters* have "anagram" counterpart characters (regardless of structure). Therefore, the reading system of Chinese readers should allow a certain amount of position flexibility of radicals in character recognition, according to Frost's (2012) hypothesis. Nevertheless, most empirical studies have supported the position-specific view of radical position coding, while only few studies suggested that the orthographic coding of radicals is flexible to some extent.

In this "experiment", I examined the extent to which a position-specific assumption and/or a position-general assumption can produce a TR effect using computer simulations. I built connectionist models that learn the print-to-sound mappings of Chinese characters via domain-general learning mechanisms. In these models, a specific behaviour emerges instead of being hardwired in. This situation allowed us to put emphasis on how the representations and processing principles interact with statistical regularities in the language environment during learning, and thus to better test the application of Frost's (2012) hypothesis to processing radicals in Chinese. The results were straightforward. The simulated TR effect was literally zero for M1 (the model based on the position-specific assumption) but was large (0.847 and 0899) for M2 and M3, indicating that the position-specific assumption of radical position representation is unable to predict a TR effect, but the position-general assumption can do so. In addition, since M1, M2 and M3 used the same functional architecture and learning rules that have been applied to English models to simulate TL effects (Lerner et al., 2014), the results suggest that similar mechanisms could be contributing to the TR effect in Chinese and the TL effect in English.

M3 only differed from M2 in that the position codings of the orthographic representation inputs were less reliable than the identity codings in M3 but were equally reliable in M2. This setting for M3 was intended to mimic the assumption in some "noisy" models that, at the early orthographic processing stage, the position information is degraded by noise and becomes less accurate. The results showed that the M3 did produce a larger TR effect, but the effect was only 0.052 or 6.2% larger than the TR effect produced by M2. This result suggests that models need not assume that the position information is extremely noisy in attempting to explain TR effects.

By testing both the left-right structure and top-bottom structure of two-radical characters, I was also able to see if the simulated TR effect was modulated by character structure. I found that, although the TR effect was smaller for the left-right structure than the top-bottom structure characters (the difference was 0.013 for M2 and 0.005 for M3), this difference was likely too small to be important. Similarly, the correlation scores between the TR/unrelated non-characters and base characters were almost the same for the two structures.

These results suggest that the models treat transposed radicals in a top-bottom character in a similar way as they treat those in a left-right character. That is, the simulation seems to suggest that the character structure doesn't impact character recognition in models that are very simple and trained with only the information of orthographic component codings, position codings and structure codings. At first sight, this result seems to be surprising because the top-bottom structure characters resemble the visuospatial configuration of Korean Hangul and one might have expected similar results (i.e., no TL type effect) for the top-bottom structure characters as is found for Hangul syllables. However, note also that, although there were codings for character structure in the orthographic representation, the visuospatial features were not described in the codings. In other words, the inputs can "tell" the model that the left-right and top-bottom characters are different structures, but the models don't really "see" the characters or "perceive" their visuospatial difference. Therefore, it is, perhaps, not entirely surprising that the results show basically no difference in simulated TR effects between the two structures even if it turns out that there is one in the empirical data.

What's also worth noting is that the simulated TR effect (the correlations between the outputs for the TR characters and the base characters were above .90, i.e., nearly perfect) appears to be quite large compared to the TL priming effect sizes versus repetition priming effect sizes, that researchers typically find in behavioural experiments. What should be realized, however, is that the models in this experiment are simplifications of the real reading situation in many ways. For example, the models only learned the print-to-sound mappings without knowing any semantic information concerning radicals and characters even though that information is an important component in normal human reading. The model architectures were also very simple compared to either the human brain or the giant networks created and designed to perform difficult tasks. Nevertheless, the models in our simulations still served the purpose of showing that a model learning the print-to-sound mappings of Chinese characters via general rules will not show a TR effect if the position coding of radical is strict, and will show a TR effect, if it is not.

Until recently, however, no TR effects have been reported in empirical studies involving Chinese readers, causing theories of Chinese word recognition to take the "position-specific view" of radical representation (e.g., Taft, 2006; Perfetti et al., 2005). At the same time, there are several issues with those previous studies, as mentioned in the Introduction. They are: (1) they inevitably involved explicit presentation of all stimuli which easily allows for post-orthographic coding affects; (2) the appearance of many radicals change when those radicals are in different positions; (3) the studies involved a mixture of characters with different structures. All of these factors could affect the results in behavioural studies. The following experiments were designed to remove those potential confounds and to directly investigate the existence of TR effects in Chinese character recognition.

2.2 Experiment 2

In Experiment 2 a masked priming lexical decision task was used in order to test whether a TR priming effect would emerge. According to the position-specific view, the same radical in different positions has different orthographic representations. Therefore, a TR prime should not give any processing head start to the target word compared to an unrelated prime. Taft's (2006) theory also postulates that there are inhibitory connections between the different position-specific units for the same radical which leads to the prediction that the TR primes may even produce an inhibition effect. However, if the orthographic coding of radicals is position-general, the expected finding is a TR priming effect in the behavioural data. Note that, as a contrast with the TR prime condition, a repetition prime condition, a condition that will assuredly produce a priming effect, was also included in this experiment as well as in Experiments 3 and 4 in which the masked priming same-different task was used. In the masked priming lexical decision task, the critical primes were presented for only 50 ms and, hence, were subliminal and unnoticeable to participants. Also, I only used left-right structure characters in this experiment and avoided changing the shapes of radicals when creating the TR stimuli.

To investigate the time window of any TR effect found and examine whether it is most likely orthographically based, EEG data were also collected in addition to collecting response latency data. The specific time windows selected for analysis were determined based on previous ERP studies and the visual inspection of the wave forms specific to the present data patterns.

Previous studies (e.g., Misra & Holcomb, 2003; Grainger et al., 2006; Holcomb & Grainger, 2006; Kiyonaga et al., 2007; Chauncey et al., 2008; Dufau et al., 2008; Ktori et al., 2014) have found four important ERP components (N/P150, N250, P325, and N400) that were modulated by various aspects of masked primes. Among them, the N/P150 component (it was negative going in the occipital area and positive going in the more anterior area, and the repetition prime enhanced the size of this component) was hypothesized to reflect the mapping of visual features onto location-specific letter identities, because a change in font between primes and targets affected repetition priming effects on this component (Chauncey et al., 2008). The N250 component, which shows up between 200 ms and 300 ms after target display in the posterior electrode sites, was thought to reflect orthographic processing because it was modulated by the orthographic nature of the prime (e.g., control primes elicited more negative waves than the TL primes) while it was not sensitive to 1-letter shifts of the prime's location (e.g., to the same target '-table-', primes 'table--', '-table-', and '--table' had same effect, with the dashes standing for spaces, Dufau et al., 2008) or font and size change (Chauncey et al., 2008). In addition to this N250 component, there was a P325 component which was also modulated by orthographic similarity and insensitive to font and size change (Chauncey et al., 2008). The latest component, N400, was only sensitive to word repetition but not to nonword repetition, so it was deemed to reflect the interaction between the whole word representation and semantics.

Partially consistent with those ideas, an early negative component (around 170 ms) has been found to reflect orthographic processing in Chinese reading. For example, using a colour matching task, Lin et al. (2011) found a left lateralized negative going component around 170 ms (N170) which was sensitive to the orthographic features of the stimuli. Using a lexical (character) decision task, Yum et al. (2015) found that the most orthographically illegal non-characters elicited a smaller positive component around 100 ms in posterior areas and a smaller negative component around 170 ms in the left posterior areas than more legal non-characters, providing further support for these ideas. These results of Chinese ERP studies showed that the effects of orthographic processing in Chinese can show up in a negative component in a very early time window, around 170 ms. This component is very similar to the N/P150 component in terms of time and polarity.

Examining ERP data in a masked priming lexical decision task, Kiyonaga et al. (2007) focused on two components (N250 and N400) modulated by repetition primes. The N250 is a negative going component that was more pronounced at posterior temporal and occipital sites within the 200-300 ms time window. The N400 is negative going and was more pronounced at the central and posterior sites within the 300-500 ms time window. These two components had been found to be modulated similarly in masked priming semantic categorization tasks in prior studies. Using the same techniques as Kiyonaga et al. (2007) but with Chinese, Su et al. (2012) showed that targets with radicals in different positions relative to their primes elicited a more negative N400 component than targets with radicals in the same positions, although the there was no difference in the occipital N170 component.

Relevant to the present discussion, Ktori et al. (2014) directly investigated the ERP difference between the TL and the SL prime conditions in a sandwich priming (Lupker & Davis, 2009) paradigm (forward mask 500 ms – 33 ms target – 50 ms prime – 500 ms target) using a lexical decision task. The results confirmed their previous findings – both adjacent (e.g., atricle–ARTICLE) and non-adjacent (e.g., actirle–ARTICLE) TL conditions elicited smaller N250 components than their corresponding SL conditions (e.g., adjacent: aqnicle, non-adjacent: aqtinle), and the adjacent TL condition also elicited a smaller N400 component than the SL condition.

The main focus of the ERP analyses in Experiment 2 was on the early negative components, arising during the first 100-250 ms, although any positive components around 300 ms after target onset were also examined. There could, of course, also be an effect in the relatively late negative component (N400), paralleling what Ktori et al. (2014) found for their adjacent TL conditions in English. This component (N400) was thought to reflect lexical-semantic processing rather than orthographic processing. In any case, it was expected that the ERP results would be broadly consistent with the behavioural results. That is, it was expected that consistent results with previous ERP studies would be found, in particular, there would be significant repetition priming effects in the N/P150 (or N170), N250 and N400 components, although the language used in the prior experiments was different. Secondly, if the TR primes produce a priming effect, it was expected that at least the earlier of these relevant components would also be modulated in the TR priming condition.

2.2.1 Method

Participants. Forty-four undergraduate students (mean age: 20.9) from Western University participated for course credit. All were right-handed native Mandarin Chinese speakers with normal or corrected-to-normal visual acuity. All participants were international students who had been in Canada for less than one year.

Materials. One hundred twenty left-right structure Chinese characters consisting of two free radicals were chosen. Sixty of them contain 2 CRs (character radicals, which are characters by themselves) and the other 60 characters contain at least 1 NCR (non-character radicals, which are not characters by themselves). The CR characters and NCR characters were matched in terms of radical stroke numbers (4.4 and 5.3 vs. 5.0 and 4.7, for the left and right radicals, respectively) and frequency (42.3 vs. 44.0 /million characters, according to the UCLA Written Chinese Corpus, 2nd edition, Tao & Xiao, 2012). One hundred twenty non-characters were created by rearranging radicals (between characters) in the 120 characters. Similar to the characters, half of 120 non-characters contain two CRs and the other half contain at least one NCR. The radical stroke numbers of non-characters were matched with those of the characters (4.3 and 5.2 vs. 5.0 and 4.8). Two hundred and forty TR primes were created by transposing the two radicals in the character and non-character stimuli. They are all non-characters. All stimuli were presented in the Song typeface and stored as bitmap image files (BMP files). The target stimuli were 100 pixels by 100 pixels in size and the prime stimuli were 80 pixels by 80 pixels in size.

There were two related prime conditions (the repetition condition and the transposed condition) and two unrelated conditions (the unrelated condition and the unrelated transposed condition). As a result, every target had 4 kinds of primes (Table 1): a repetition prime, a transposed radical prime, an unrelated prime, and an unrelated transposed radical prime. The unrelated prime-target pairs were created by re-pairing the primes and targets in both the TR and repetition prime conditions. There were 960 (4 * 240) prime-target pairs in total. These pairs were divided into 4 lists, so that each target appeared only once in each list, each list had the same number of pairs in each condition and each participant received only one list. The order of trials in a list was randomised for each participant.

Table 1: Examples of four types of prime-target relationship.

Prime-target relationship	Example	
	Prime	Target
Related, not transposed (Repetition)	如	如
Unrelated, not transposed	规	如
Related, transposed		如
Unrelated, transposed		如

Procedure. The experiment involved a masked priming lexical decision task. Participants were asked to judge whether the target character was a real character or not. Each trial began with a mask consisting of random strokes (500 ms), followed by the prime (50 ms), and finally the target, which remained on the screen for 2.5 seconds or until the participant made a response. The software E-prime 2.0 (Psychology Software Tools, Inc.) was used to program the experiment and collect reaction time and accuracy data. During the experiment, the instructions and any conversations between the experimenter and the participant were all in Chinese.

The EEG data were recorded through the Active Two Biosemi system with a 32-channel cap. The electrodes were arranged using the standard International 10-20 system. Electrooculogram (EOG) activity was recorded from active electrodes placed above, beside, and beneath the left eye, and beside the right eye. An additional active electrode (CMS, common mode sense) and a passive electrode (DRL, driven right leg) were used to create a feedback loop for amplifier reference. Two additional electrodes were placed at the left and right mastoids for offline re-reference[5].

[5] Biosemi uses a non-standard referencing system which replaces the "ground" electrodes with the Common Mode Sense (CMS) and the Driven Right Leg (DRL) passive electrodes. With this type of system, we should always reference the data to electrodes other than CMS. See https://www.biosemi.com/faq/cms&drl.htm for more information.

EEG data was preprocessed in the MATLAB version 2020a (The MathWorks, Inc.) environment using routines implemented in EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014). Data were filtered offline with a high-pass 0.1 Hz filter and a low-pass 30 Hz filter and re-referenced to left and right mastoids. Epochs ranging from -200 to 800 ms relative to the onset of targets were extracted from the continuous recoding. Epochs with incorrect responses, as well as epochs with activity exceeding ±75 V at any electrode site were discarded. Independent components responsible for eye movements and blinks were identified from an independent component analysis (using the fastica algorithm implemented in EEGLAB) and subsequently removed. Baseline correction was applied in relation to the 200 ms of pre-stimulus activity. After all these steps, all remaining epochs were averaged by condition and for each participant.

2.2.2 Results

2.2.2.1 Behavioural analyses

Data based on the following situations were excluded from further behavioural data analysis: (1) One participant whose error rate was higher than 75%; (2) Six items that had a mean response accuracy lower than 50% across all participants; (3) Ten participants whose EEG data was poorly recorded. Then, latencies for incorrect responses were excluded from the latency analyses, as were latencies that were shorter than 200 ms or longer than 2000 ms (10.43% of all data). Note also that only the data from trials involving character targets were analysed.

The latencies of correct responses and the error rates for the character targets were analysed using generalized linear mixed-effects models (GLMMs) in R version 4.1.2 (R Core Team, 2021) and RStudio 1.4.1106 (RStudio Team, 2021), treating subjects and items as random effects and treating prime-target relatedness (related vs. unrelated), transposition (repetition vs. transposition), and radical type (CR character vs. NCR character) as fixed effects. The R package “lme4” version 1.1-27 (Bates, Maechler, Bolker, & Walker, 2015) was used to fit the GLMMs with the maximum likelihood method using the Laplace approximation. To test the significance of each fixed effect and interaction, the "anova" function from the R package "car" version 3.0-10 was used. When fitting models, the appropriate contrast coding (i.e., contr.sum) was used for factors that are included in interactions instead of the R's default contrast coding (contr.treatment). Post-hoc analyses were conducted by using the R package "emmeans" version 1.6 (Lenth, 2021), with the Holm method to control for family-wise error rate. The mean lexical decision latencies (in milliseconds) and percentage error rates across participants are shown in Table 2.

Table 2: Mean lexical decision latencies (reaction times [RTs], in milliseconds) and percentage error rates (in parentheses) for character targets in Experiment 2.

	CR characters				NCR characters			
	Repetition		Transposed		Repetition		Transposed	
Related	573	(4.51)	622	(5.75)	566	(6.79)	604	(5.94)
Unrelated	631	(5.36)	652	(6.74)	619	(8.07)	621	(9.69)
Priming	*58*	*(0.85)*	*30*	*(0.99)*	*53*	*(1.28)*	*17*	*(3.75)*

The Gamma distribution was used with an identity link between fixed effects and the dependent variable to fit GLMMs for the latency analyses. The model for the latency analysis was: RT ~ Relatedness * Transposition * Radical_Type + (1 | Subject) + (1 | Item). To fit GLMMs for the error rate analyses, the binomial distribution with the logistic link function was used. The model for the error rate analysis was: ACC ~ Relatedness * Transposition * Radical_Type + (1 | Subject) + (1 | Item).

Latencies (character targets). When fitting models with the default optimizer, the program sometimes produced convergence warnings. To limit the occurrence of convergence failures, the random factors in the models were kept as simple as possible by using only random intercepts for subjects and items. However, there were still a number of convergence failures, which frequently occur when using the lme4 package, especially for GLMMs, although many of these convergence warnings are false positive. In our analysis, after switching to the BOBYQA optimizer, the convergence warnings were gone. Hereafter, I chose to report results from models fitted using the BOBYQA optimizer if the initial fitting with the default optimizer failed to converge.

There were significant main effects of prime-target relatedness ($\chi^2(1) = 87.44$, $p < .001$) and transposition ($\chi^2(1) = 33.55$, $p < .001$), but the main effect of radical type was not significant ($\chi^2(1) = 0.16$, $p = .69$). The responses were faster when the target was preceded by a related prime than when preceded by an unrelated prime and when the character contained one NCR character than when it did not. The only significant interaction was the interaction between prime-target relatedness and transposition ($\chi^2(1) = 20.25$, $p < .001$). Post-hoc tests showed that the difference between related and unrelated conditions in both the repetition and transposed conditions were significant (the former is the masked repetition priming effect, and the latter is a masked TR priming effect), although, as expected, the repetition priming effect was stronger than the TR priming effect (repetition priming: $z = 10.52$, $p < .001$; TR priming: $z = 3.54$, $p < .001$).

Error rates (character targets). The main effect of prime-target relatedness was significant ($\chi^2(1) = 5.12$, $p = .020$), with the error rates on unrelated trials being higher than the error rates on related trials. Neither the main effects of transposition, the main effect of radical type nor any interaction was significant (all *p*s > .10).

2.2.2.2 ERP analyses

ERPs from 32 scalp channels (Figure 3) time-locked to the onset of targets are plotted in Figure 4 (NCR characters, repetition priming), Figure 5 (CR characters, repetition priming), Figure 6 (NCR characters, TR priming) and Figure 7 (CR characters, TR priming).

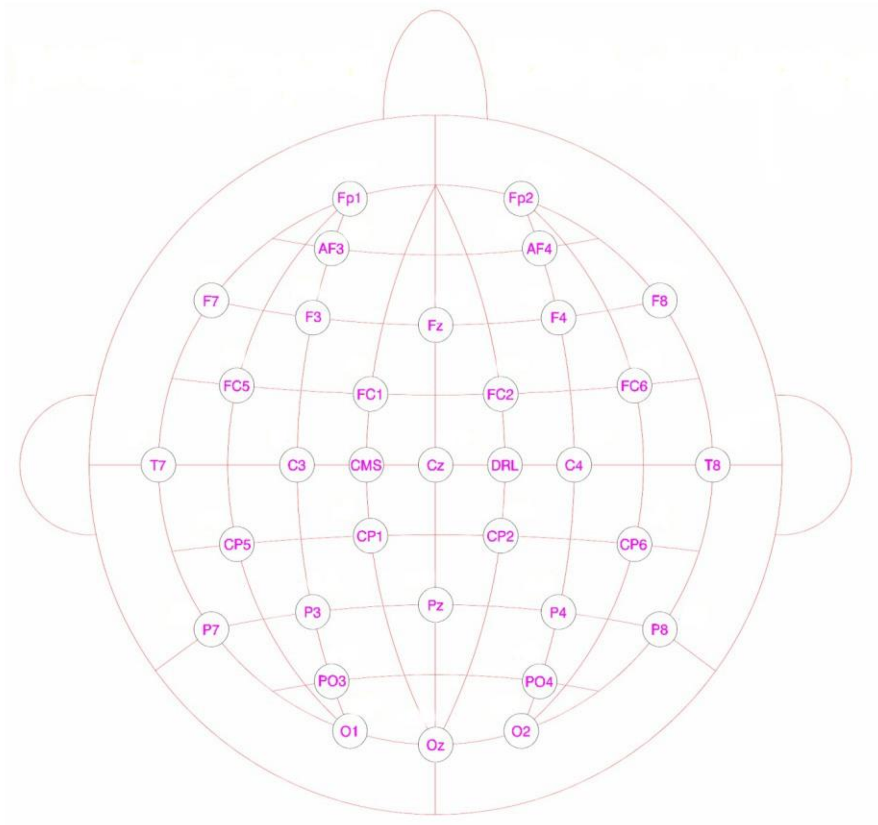

Figure 3: BioSemi layout 32+2 electrodes. Data from all electrodes except for CMS and DRL were used in the analyses in Experiments 2 and 3.

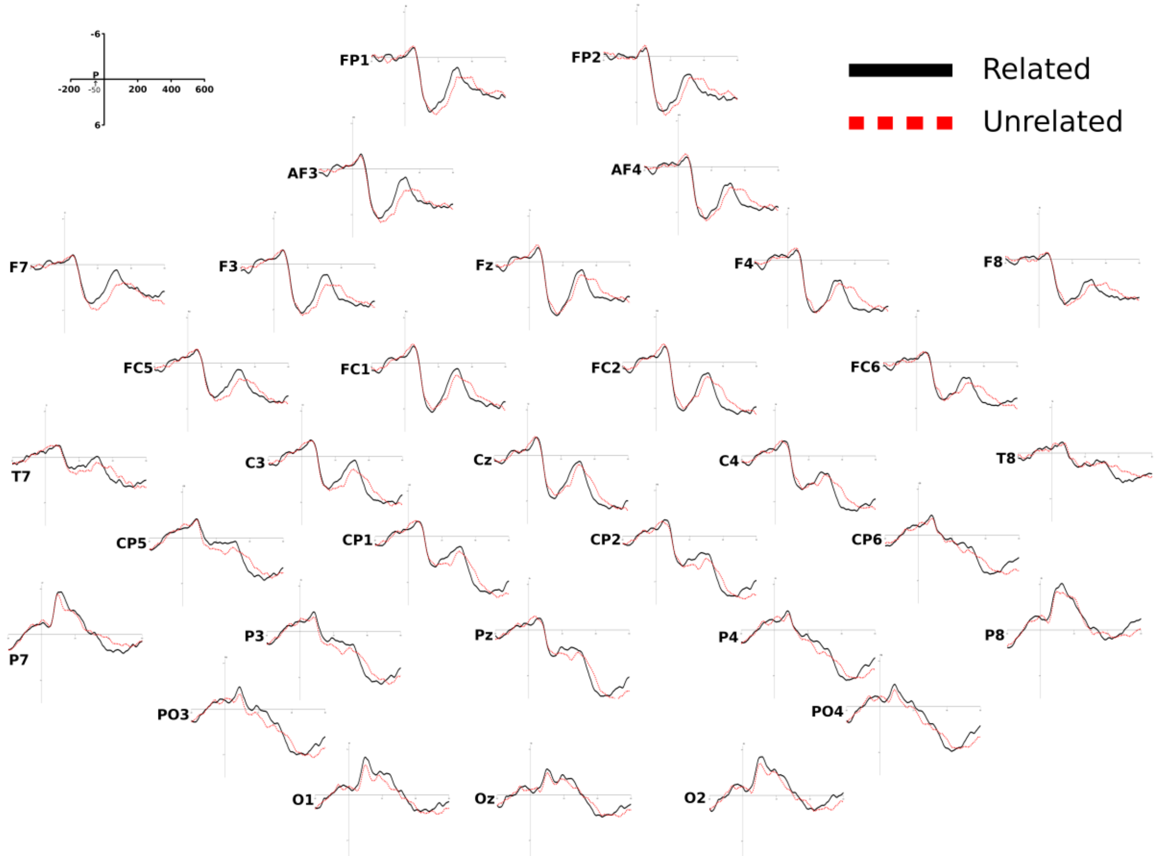

Figure 4: ERPs from all 32 scalp channels time-locked to the onset of NCR character targets in the repetition (black solid) and unrelated (red dotted) conditions in Experiment 2.

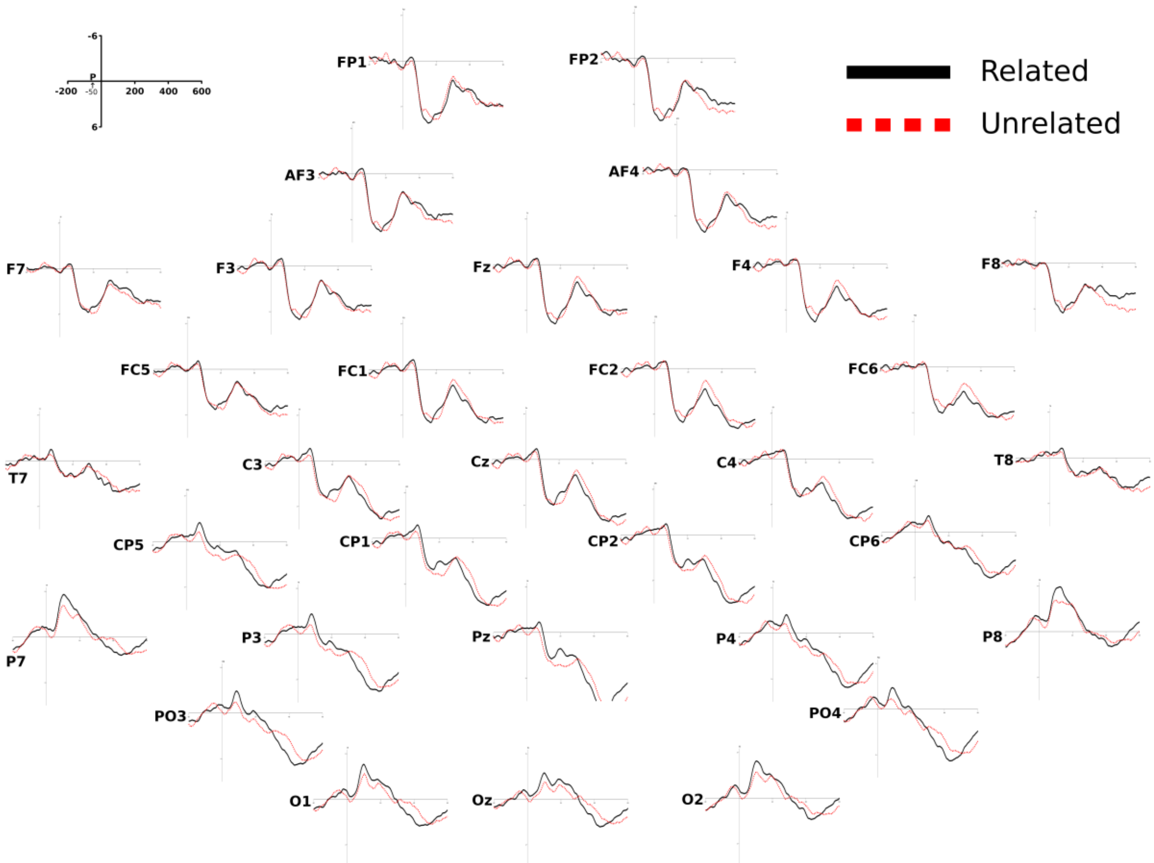

Figure 5: ERPs from all 32 scalp channels time-locked to the onset of CR character targets in the repetition (black solid) and unrelated (red dotted) conditions in Experiment 2.

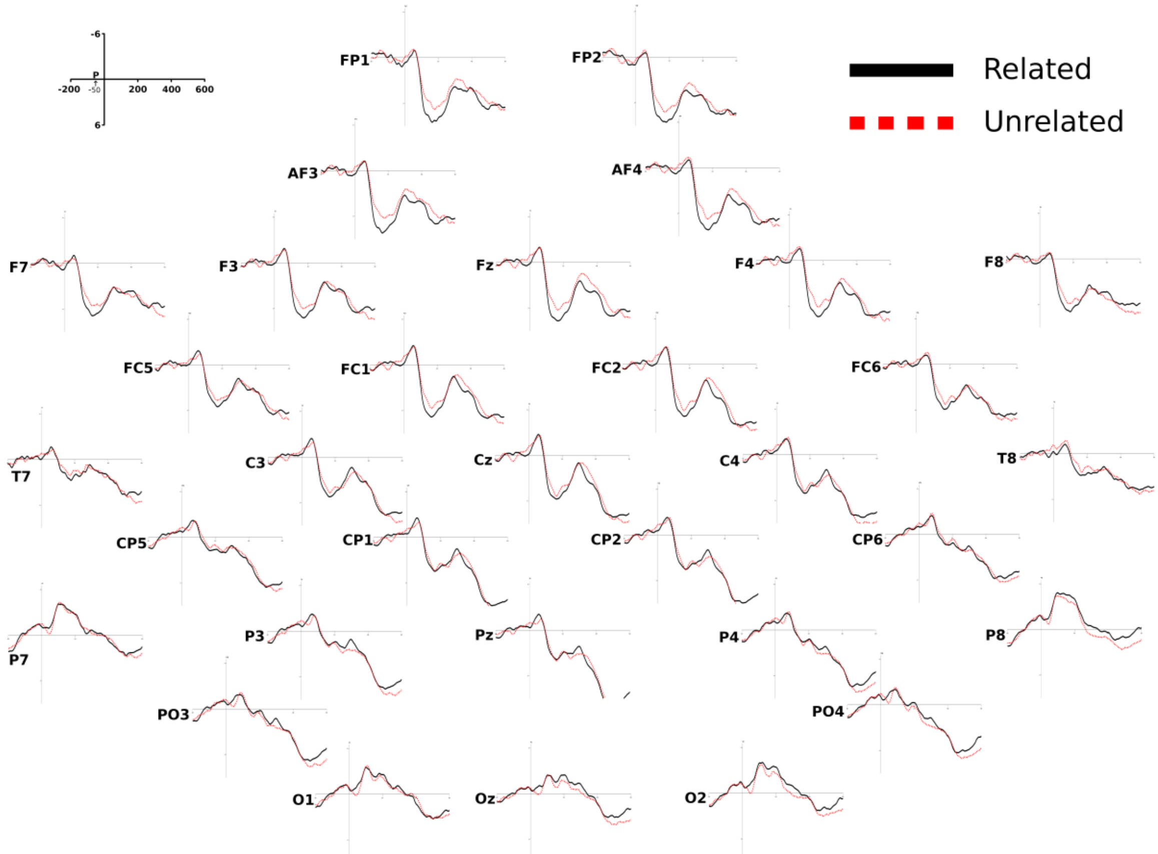

Figure 6: ERPs from all 32 scalp channels time-locked to the onset of NCR character targets in the transposed (black solid) and unrelated (red dotted) conditions in Experiment 2.

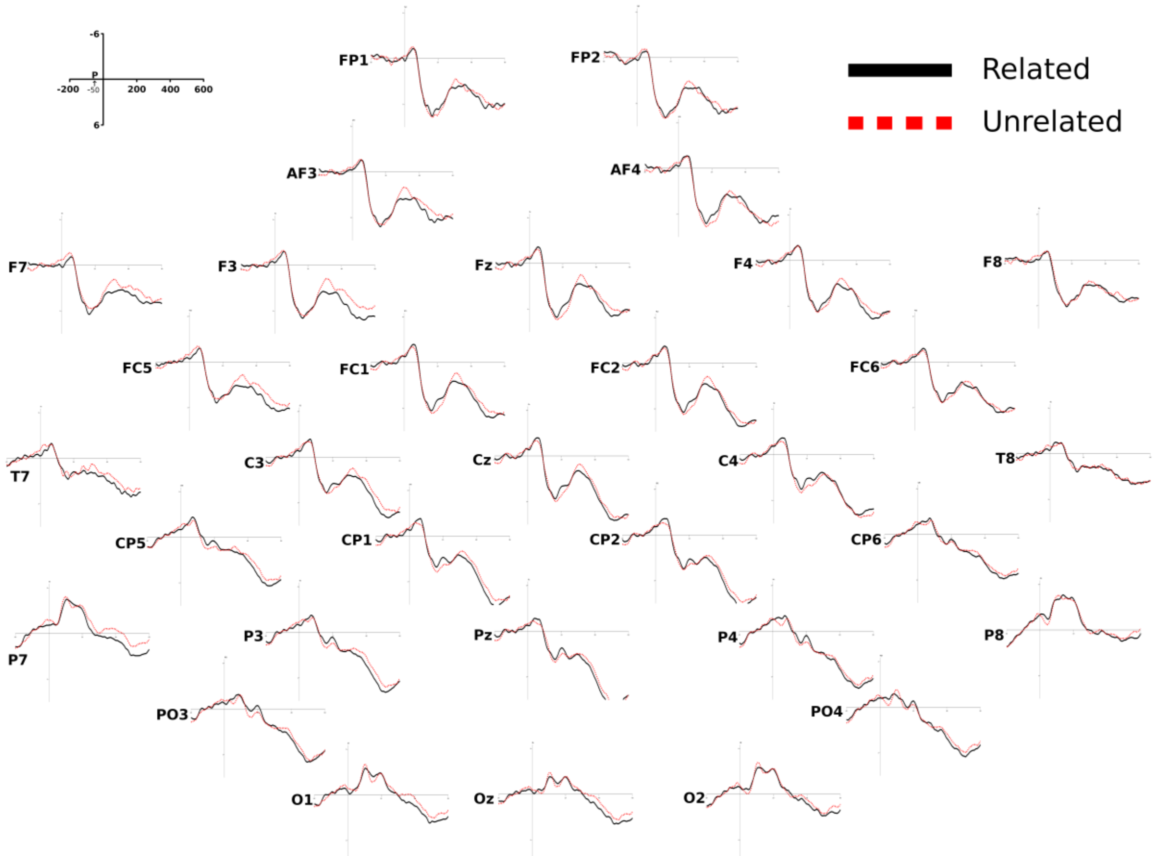

Figure 7: ERPs from all 32 scalp channels time-locked to the onset of CR character targets in the transposed (black solid) and unrelated (red dotted) conditions in Experiment 2.

From a visual inspection of the repetition vs. unrelated waves for NCR characters at all 32 sites, shown in Figure 4, it can be seen that there was a negative component in the occipital area (e.g., Figure 8A, 8B) around 100 ms after target onset. This component was more negative for the related condition, as was also true for the N150 component found by Grainger and colleagues (e.g., Dufau et al., 2008). Closely following this negative component, there was a small second negative component around 200 ms in the occipital area (e.g., Figure 8A, 8B). In the parietal and posterior area, there was a positive going component around 240 ms (e.g., Figure 8C). After this component, there was a negative going component (N300) around 300 ms in most of the channels and it was more negative for the unrelated than the repetition condition (Figure 8D). Similar patterns were also there for the repetition vs. unrelated waves of CR character targets (Figure 9), although the N300 for CR characters was more distributed to the left posterior area (Figure 10).

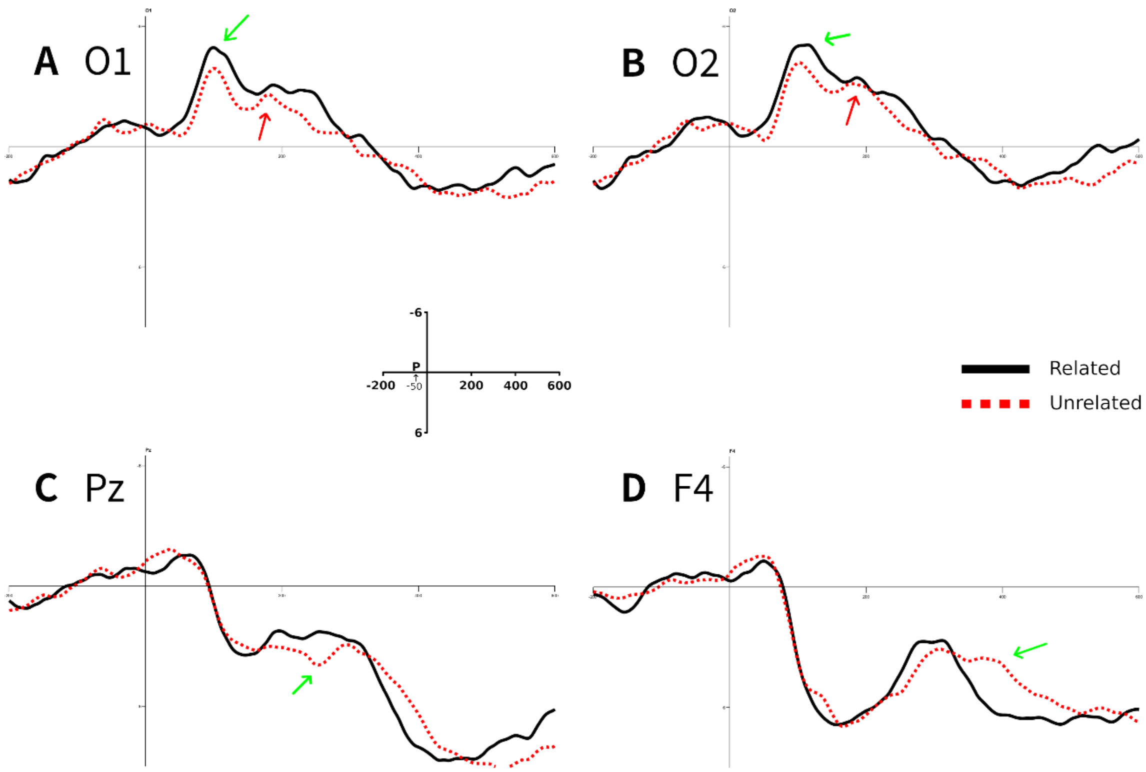

Figure 8: The O1, O2, Pz, F4 sites from Figure 4. (A & B) the green arrow denotes an early negative component around 100 ms after target onset, the red arrow denotes a negative component around 200 ms; (C) the green arrow denotes a positive going component around 240 ms; (D) the green arrow denotes a negative going component (N300) around 300 ms.

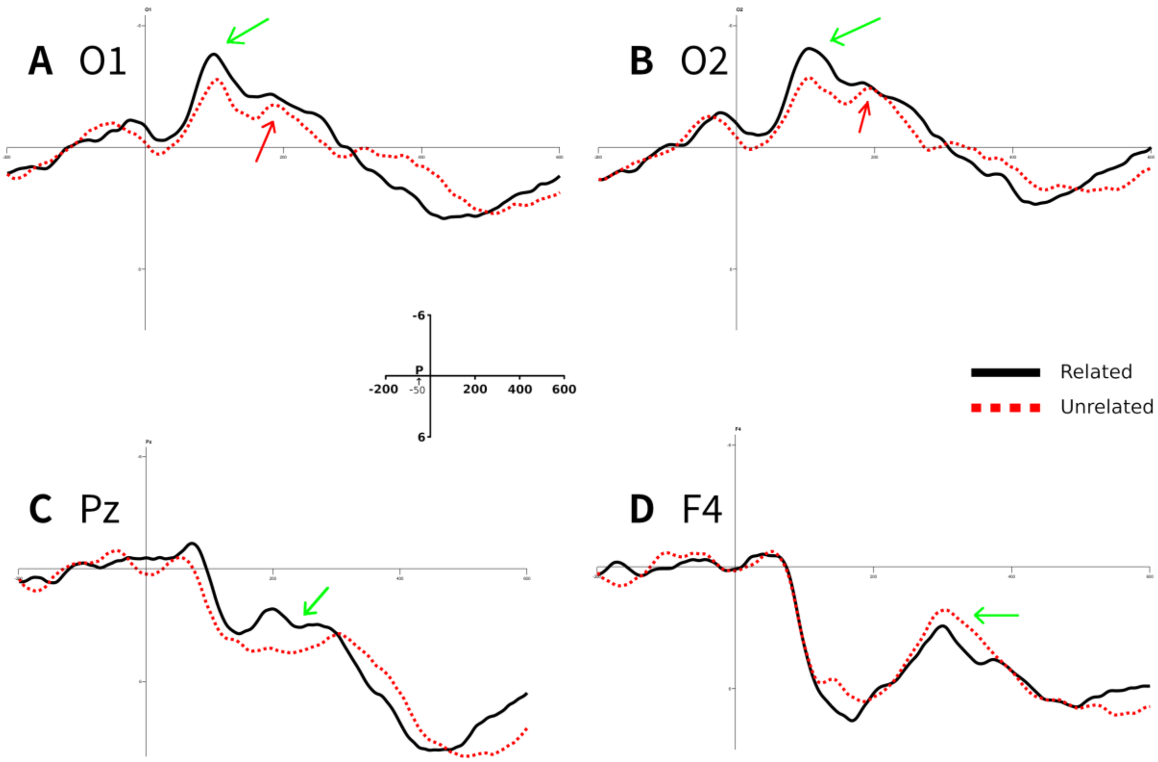

Figure 9: The O1, O2, Pz, F4 sites from Figure 5. (A & B) the green arrow denotes an early negative component around 100 ms after target onset, the red arrow denotes a negative component around 200 ms; (C) the green arrow denotes a positive going component around 240 ms; (D) the green arrow denotes a negative going component (N300) around 300 ms.

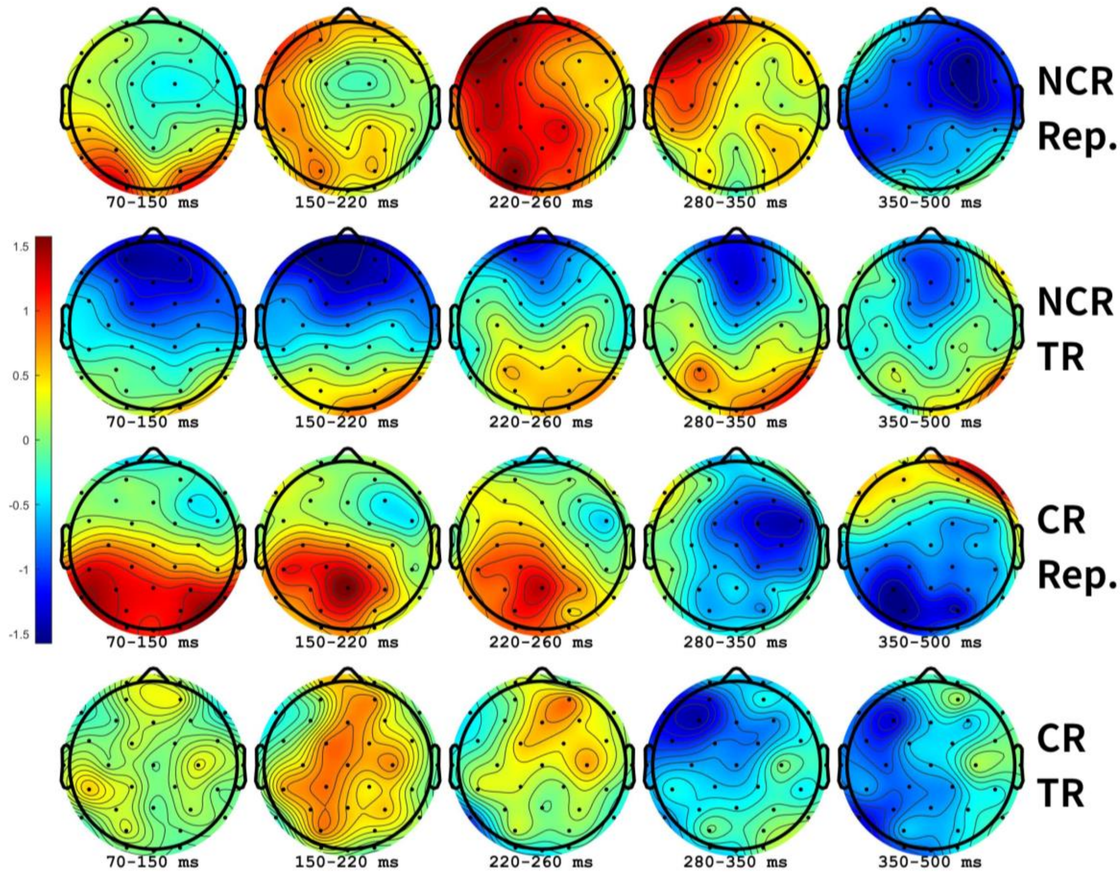

Figure 10: Scalp maps of the difference of the mean amplitude of waveforms between the unrelated and related conditions (unrelated – repetition/TR) from 70 to 350 ms for the NCR and CR character targets in Experiment 2.

From visual inspection of the transposed vs. unrelated waves (Figures 6 and 7), it seemed that there was no N150 difference between the two conditions in the occipital area during the first 150 ms of target onset (Figure 11A). Instead, there was a positive going component in the frontal area around 170 ms which was more positive for the unrelated condition then the related condition (Figure 11A). However, this effect was only obvious for the NCR characters (e.g., Fz site in Figure 6) not the CR characters (e.g., Fz site in Figure 7). Like the repetition condition, there was a positive going component around 240 ms in the central-posterior area (Figure 11B). Finally, there was a large negative component around 300 ms in the central anterior area, but it was slightly more negative for the unrelated condition than the transposed condition for the CR character targets (e.g., the Cz site, see Figure 12).

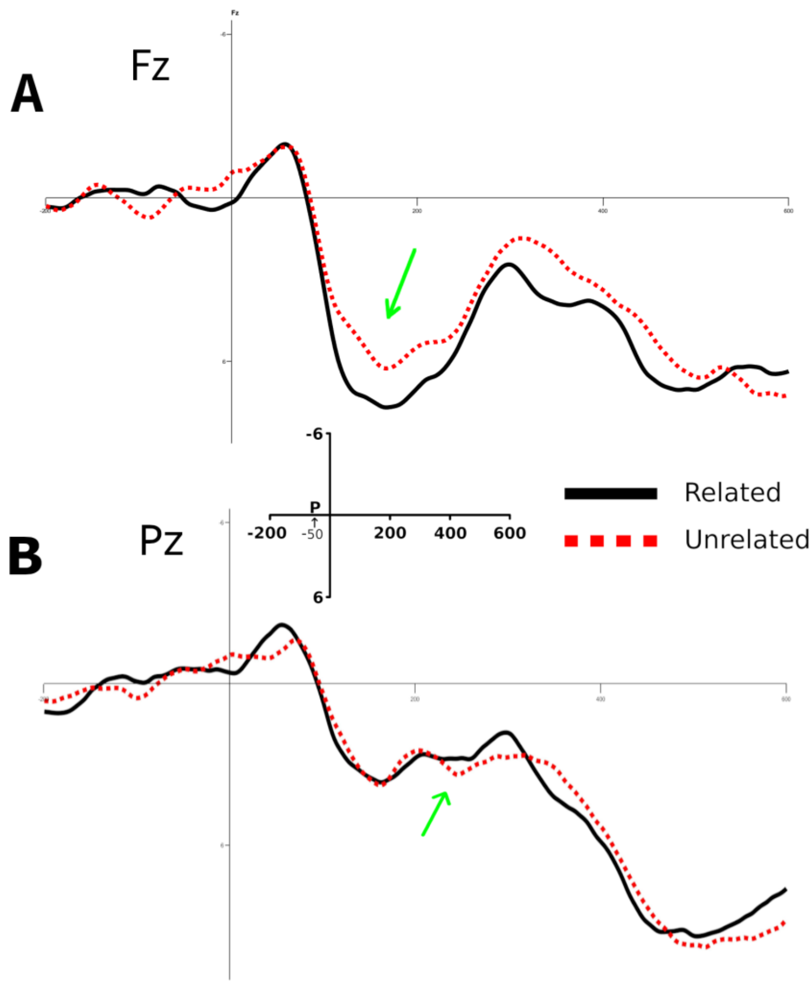

Figure 11: The Fz, Pz sites from Figure 6. (A) the green arrow shows that there was a positive going component in the frontal area around 170 ms; (B) the green arrow denotes the positive going component.

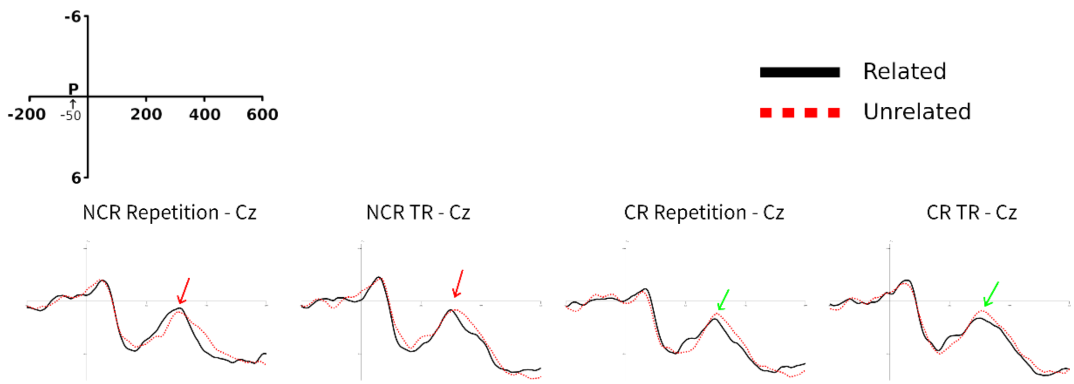

Figure 12: Waveforms for the Cz site in all four conditions in Experiment 2. The green arrow shows the negative component around 300 ms was more negative for unrelated condition for the CR character targets.

Based on the results of previous studies and the visual inspections of the wave forms, three time windows were chosen: 70-150 ms, 150-220 ms, 220-260 ms, and 280-350 ms. The first time window was for the analysis of early negative component in the occipital area. The second time window was for the analysis of the positive going component around 170 ms in the frontal area. The third time window was for the analysis of the positive going component around 240 ms. The last time window was for the analysis of the last negative component which appeared 300 ms after target onset. In an effort to capture distributional effects in these data while minimizing the number of comparisons, the 32 head channels were grouped into three separate areas along the anteroposterior axis of the head (see Figure 13). The mean amplitudes (or the peak latencies for the analysis in the last time window in Experiment 3) in each of the three areas were analysed in separate ANOVAs.

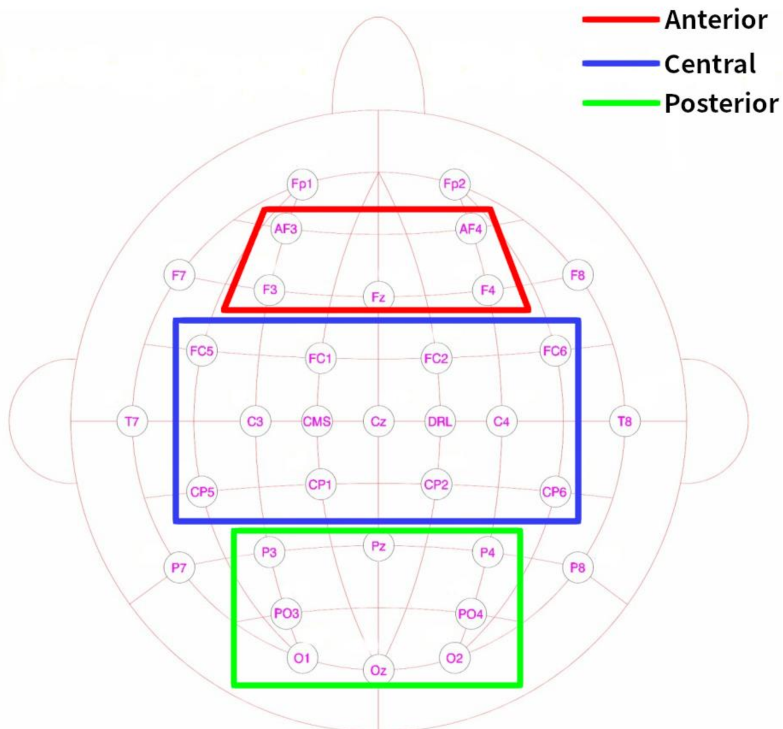

Figure 13: The three area groups of electrode sites used for the ANOVAs in Experiment 2.

70 to 150 ms target epoch. *For the repetition condition*: There was a main effect of Relatedness in the posterior area [$F(1, 31) = 6.73$, $p = .014$]. The repetition condition elicited more negative response than the unrelated condition. There was no effect of Radical Type in the central and posterior areas (all *p*s > .05). The two-way interaction between Relatedness and Radical Type was not significant in any of the three areas (all *p*s > .30).

For the transposed (TR) condition: There was no main effect of Relatedness or Radical Type (all *p*s > .10). The two-way interaction between Relatedness and Radical Type was marginal in the anterior area ($p = .06$) while not being significant in the other two areas (both *p*s > .20). If divided the data by Radical Type in the anterior area, the TR effect was only significant for the NCR characters (NCR: $p = .02$, CR: $p = .80$).

150 to 220 ms target epoch. *For the repetition condition*: There was no main effect of Relatedness or Radical Type (all *p*s > .10). The main effect of Radical Type and the two-way interaction between Relatedness and Radical Type was not significant either (all *p*s > .50).

For the transposed (TR) condition: There was no main effect of Relatedness or Radical Type (all *p*s > .20). The two-way interaction between Relatedness and Radical Type was marginal in the anterior area (*p* = .07) while not being significant in the other two areas (both *p*s > .15). If divided the data by Radical Type in the anterior area, the TR effect was only significant for the NCR characters (NCR: *p* = .02, CR: *p* = .57).

220 to 260 ms target epoch. *For the repetition condition*: There was a main effect of Relatedness in the posterior area [$F(1, 31) = 4.83$, $p = .036$]. The unrelated condition elicited more positive response than the repetition condition. The two-way interaction between Relatedness and Radical Type was not significant in any of the three areas (all *p*s > .35).

For the transposed (TR) condition: There was no main effect of Relatedness or Radical Type (all *p*s > .40). The two-way interaction between Relatedness and Radical Type was not significant either (all *p*s > .30).

280 to 350 ms target epoch. *For the repetition condition*: There was no main effect of Relatedness or Radical Type (all *p*s > .09). The two-way interaction between Relatedness and Radical Type was not significant either (all *p*s > .10).

For the transposed (TR) condition: There was no main effect of Relatedness or Radical Type (all *p*s > .14). The two-way interaction between Relatedness and Radical Type was not significant either (all *p*s > .20).

2.2.3 Discussion

In Experiment 2, a significant interaction between relatedness and transposition was found. The difference between the repetition condition and the unrelated condition was

58 ms. This repetition priming effect indicated that the masked priming manipulation was successful in Experiment 2. The effect that was more relevant to the present investigation involved the contrast between the transposed radical condition and its parallel unrelated condition. If the representation of a radical can be activated by the same radical in different positions, then the transposed radical primes should be more helpful than the unrelated primes for the participants in making a lexical decision. Indeed, this critical effect was found in Experiment 2.

The masked priming lexical decision task was used in which the critical primes are subliminal and thus can prevent the use of any prime-based strategy that might reduce late effects in the behavioural data. This manipulation in Experiment 2 was the same as that used in their Experiment 3 by Ding et al. (2004) who didn't find a significant difference between their condition in which a radical was in the opposite position and the unrelated condition. However, they did find an 11 ms facilitation effect, contrasting with a facilitation effect size of 23 ms between the condition in which the shared radical was in the same position and the unrelated condition. At least part of this difference could be a result of the fact that the same radical has different sizes when it's on the left versus right side of a character.

In Experiment 2, because the same images of two radicals in a character were used to create the prime in the transposed radical condition, their size and shape remained unchanged. Also, the transposed radical primes contained both radicals that are in the target, albeit in opposite positions, which should result in a larger effect size than Ding et al.'s (2004), if the primes do have an impact. In addition, I only used the left-right structure characters as stimuli in order to avoid the mixture of characters with different structures (another potential issue in previous studies). The results showed that, when these potential issues are controlled, a clear TR effect can be found in the masked priming lexical decision task.

Another thing worth noting is that the TR effect was not significantly affected by the radical type for left-right structure characters, although the TR priming effect was numerically smaller for the NCR characters. This finding indicates that the representations of radicals is the same regardless of whether a radical is also a character (containing meaning by itself) or not. Although it was expected that NCR radicals, which can only exist in a character in combination with another radical, might be more position specific than CR radicals, there was little evidence that such was the case.

Concerning the ERP data of Experiment 2, the ANOVA results are summarised in Table 3. The first thing to note is that there was significant main effect of Relatedness for the repetition condition as early as the first time window, while there was no significant main effect of Relatedness for the TR manipulations in any time window. There were only two marginal interactions in the first two time windows for the TR condition. If we divide the data by Radical Type, the TR effect was only significant for the NCR characters in the first two time windows, which was contradictory to expectation that the TR effect should be more easily discovered for the CR characters since the positional information is not intrinsic to their representations (i.e., they can appear in either the left or right position). If we compare the significant and marginal effects that involve the factor Relatedness for the repetition and TR conditions, it seems that both the repetition and TR effects (columns involving Relatedness) showed up as early as the first time window, but the effects in the TR condition were much weaker.

Table 3: ERP ANOVA results of Experiment 2. Each asterisk in the table indicates a significant ($p < .05$) main effect or interaction and each plus indicates a marginal effect ($.05 < p < .10$).

Time Window	Area	Repetition			TR		
		Relatedness	Rad_Type	Relatedness × Rad_Type	Relatedness	Rad_Type	Relatedness × Rad_Type
Window 1 70-150 ms	Anterior		+				+
	Central		+				
	Posterior	*					
Window 2 150-220 ms	Anterior						+
	Central						
	Posterior	+					
Window 3 220-260 ms	Anterior						
	Central						
	Posterior	*					
Window 4 280-350 ms	Anterior						
	Central		+				
	Posterior						

To summarise the ERP results more specifically, there was a repetition priming effect in an early negative component (the repetition condition was more negative) approximately 100 ms after target onset in the occipital area. This posterior negative component was considered to be the N/P150 component found in previous masked priming ERP studies. It is thought that this component reflects a processing stage in which visual features of stimuli are mapped onto higher level representations. Considering the very early time window and the fact that this component is sensitive to font changing and 1-letter position shifting of the prime (Dufau et al., 2008), it is thus hypothesized to reflect the mapping of visual features onto letter identities. The result in Experiment 2 that there was no TR priming effect in the occipital area in this component supports this idea. Because the radicals were transposed in TR primes, the radical pattern was visually different from that of the targets. In this experiment, this component could be thought to reflect the processing involved in forming radical representations from the visual features of the input. Note that the fact that this component is insensitive to radical transposition doesn't mean that at this stage the radical representation is position specific. If, as hypothesized, this component is sensitive to visual features, one would expect that the TR and unrelated primes, both of which are visually different from the repetition prime and the target would behave similarly. There was also a repetition priming effect in a positive component (unrelated condition was more positive) in the occipital area around 240 ms. The following N300 component in the central anterior area showed no priming effect for either the repetition or TR condition.

The basically null TR effect in all time windows means that the ERP data provide very little useful information concerning the time at which the TR effect emerged. There might be a power issue in Experiment 2, however, because only the data from 33 participants were kept for the ERP analysis as a result of the quality of the EEG data. Beside the potential low power, the task used in Experiment 2 was the masked priming lexical decision task which is known to be affected by a number of nonorthographic factors. First, the repetition primes and the targets shared phonology whereas the TR primes were non-characters and had no phonological overlap with the targets. Phonology may have played a relatively important role in producing priming in this experiment. Second, the repetition primes had semantic overlap with the target characters, which could also benefit the recognition of the targets while, again, such was not the case for the TR primes and targets. The TR primes only benefit the processing of targets in terms of orthography. This difference between TR and repetition primes may have increased the difficulty in finding a consistent pattern in the ERP data for the TR condition in this task.

In any case, the pattern of ERP results in Experiment 2 is not, at this point, informative which could be due to the complex nature of the lexical decision task. Therefore, in order to diminish any potential effects of phonology and semantics, effects that do arise in lexical decision tasks, a more orthographically oriented paradigm was used in Experiment 3, potentially allowing a closer look at the origin of TR priming effect through ERPs.

2.3 Experiment 3

In Experiment 3, a different paradigm, the same-different matching task, was combined with the masked priming technique. In the lexical decision task, it is well known that different types of priming effects can be found for word targets (e.g., form priming, phonological priming and morphological priming). Therefore, that task does not allow an uncontaminated examination of the nature of the orthographic coding process. Essentially, the situation created in Experiment 2 was like priming the English word “at” with the nonword “ta” with respect to the visual aspects, as well as priming the word “honeymoon” with “moonhoney” with respect to the morphological/phonological aspects, because the Chinese radicals carry a certain amount of semantic/phonology information. To rule out the morphological or phonological impact of radicals, we need to use tasks that are less affected by them.

The same-different matching task is one such task as it has been thought to be based mostly on orthographic level processing (some advocates argue that it is purely based on orthographic codes, but see Lupker, Nakayama, et al. (2015, 2018), Lupker, Perea, et al. (2015), Yang et al. (2020) for evidence of at least a small contribution from phonology). In the masked priming version of this task, participants are displayed with, in sequence, a visible reference stimulus, a very brief prime, and a target stimulus on each trial. They are asked to decide whether the reference and target are the same or not. The reason that it appears to be essentially an orthographically based task is that in behavioural studies using this task there are priming effects for nonword targets on the trials when the first stimulus (the reference stimulus) and the final stimulus (the target) match (the “same” trials), while in the lexical decision task it is uncommon to find priming effects for nonword targets. This difference suggests that performance in the same-different matching task is less lexically based, thus seemingly making it a better task than the lexical decision task for studying the orthographic coding process.

As in Experiment 2, one would expect to find a TR priming effect in the behavioural data if the orthographic coding of radicals is position general. With respect to the ERP data, the pattern of ERP results could be altered qualitatively by changing the task, just as the pattern changes somewhat in the behavioural results when using the masked priming same-different matching task instead of the masked priming lexical decision task (Norris et al., 2018). However, as Kiyonaga et al.'s (2007) results have shown, the relevant components can still be similar when using different tasks (i.e., in their case, the lexical decision task versus a task involving monitoring for animal words).

Note, however, that the primary goal of this experiment is not to compare the ERP patterns obtained in the masked priming lexical decision and masked priming same-different matching tasks and then look for any qualitative difference. Instead, it is to investigate the TR effect and look for ERP evidence to determine whether the TR effect, if any, is orthographically based. Therefore, the ERP analyses of Experiment 3 will still mainly focus on the components in the early time windows. Note that the time windows used may be different from those in Experiment 2 since the response latencies are expected to be shorter in Experiment 3 due to the task being less difficult than the task of making a lexical decision. In any case, it was expected that the ERP results would be consistent with the behavioural results, in that, as in Experiment 2, there will be a TR priming effect and the ERP components will be modulated by the priming condition in a way that is consistent with that effect.

2.3.1 Method

Participants. Thirty-three undergraduate (mean age: 19.7) students from Western University participated for course credit. All were right-handed native Mandarin Chinese speakers with normal or corrected-to-normal visual acuity who had been in Canada for less than one year.

Materials. The one hundred twenty characters from Experiment 2 were used as targets on the "same" trials. Another 240 characters were chosen as the reference and target stimuli for the "different" trials. Targets in "same" and "different" trials and reference stimuli in "different" trials were matched on frequency (same:166.58, different: 124.89, reference: 157.66, $F(2, 357) = 0.48$, $p = .62$) and stroke numbers (same: 9.69, different: 10.07, reference: 10.35, $F(2, 357) = 1.58$, $p = .21$). The target and the reference stimulus were the same character on the "same" trials and different characters on the "different" trials. The unrelated primes were again created by re-pairing the related primes and targets. The 4 prime types were the same as Experiment 2 as was the list construction for the "same' trials.

On the "different" trials, a "zero contingency" scenario (Kinoshita & Norris, 2010; Perea et al., 2011) was used, in which the related primes were related to the reference stimulus rather than the target in order to eliminate the (somewhat unlikely) possibility of participants using the prime strategically. That is, if the prime were related to the target, then only in the related condition on "same" trials would the prime be the same as the reference stimulus. Hence, participants would therefore be biased to make a "same" response based on the reference-prime relationship, which could artificially produce a priming effect on "same" trials. Another benefit of using a "zero contingency" scenario is that it gives us an extra chance to investigate the priming effect on "different" trials, because an inhibitory effect is typically observed on the "different" trials when the reference and prime are orthographically similar (e.g., Perea et al., 2011). However, although this inhibitory effect was successfully demonstrated by Perea et al. (2011), it tends to be smaller than the effect on the "same" trials. The order of trials was randomized for each participant.

Procedure. Each trial began with a reference character above a mask consisting of random strokes. Both stimuli were presented for 1000 ms. Then the reference stimulus was removed from the screen and the mask was replaced by the prime, which remained on the screen for 50 ms. After the prime disappeared, the target character was presented in the same position as the prime and remained on the screen for 3 seconds or until the participant responded (the target stimuli were 100 pixels by 100 pixels in size and the prime stimuli were 80 pixels by 80 pixels in size). Participants were asked to indicate whether the target character was the same as the reference character or not by pressing one of two buttons. The software E-prime 2.0 (Psychology Software Tools, Inc.) was used to program the experiment and collect reaction time and accuracy data. During the experiment, the instructions and any conversations between the experimenter and the participant were all in Chinese.

The EEG data was recorded through the Active Two Biosemi system with a 32-channel cap. The setting of the device and electrodes and the data preprocessing were the same as in Experiment 2.

2.3.2 Results

2.3.2.1 Behavioural analyses

Analyses excluded data from one participant due to poor ERP recording, leaving 32 participants in the final sample. The average error rate was 2.6% across participants and there was no item with a high error rate. Latencies for incorrect responses were excluded from the latency analyses, as were latencies that were shorter than 200 ms or longer than 2000 ms (3.1% of all data). The latencies from the correct trials and the error rates for the "same" trials were analysed using GLMMs. The mean response latencies (in milliseconds) and percentage error rates are shown in Table 4.

Table 4: Mean response latencies (reaction times [RTs], in milliseconds) and percentage error rates (in parentheses) in Experiment 3.

		CR characters				NCR characters			
		Repetition		Transposed		Repetition		Transposed	
Same	Related	520	(2.92)	538	(3.15)	522	(3.98)	534	(2.72)
	Unrelated	583	(3.35)	565	(2.29)	574	(6.08)	567	(3.36)
	Priming	*63*	*(0.43)*	*27*	*(-0.86)*	*52*	*(2.10)*	*33*	*(0.64)*
Diff	Related	626	(1.68)	615	(1.47)	631	(1.67)	634	(1.69)
	Unrelated	605	(1.05)	614	(1.05)	600	(2.10)	620	(1.05)
	Priming	*-21*	*(-0.63)*	*-1*	*(-0.42)*	*-31*	*(0.43)*	*-14*	*(-0.64)*

The latencies and error rates were analysed using GLMMs using the same method and packages as in Experiment 2. The models used to fit the GLMMs was also the same as in Experiment 2, since the fixed and random effect factors are the same in both experiments.

Latencies for the "same" trials. There was a significant main effect of prime-target relatedness ($\chi^2(1) = 109.10$, $p < .001$), however, neither the main effect of transposition nor that of radical type were significant (transposition: $\chi^2(1) = 0.18$, $p = .67$; radical type: $\chi^2(1) = 0.20$, $p = .66$). The responses were faster when the target was preceded by a related prime than when preceded by an unrelated prime. There was only one significant interaction, the interaction between the prime-target relatedness and transposition ($\chi^2(1) = 10.19$, $p = .001$). Post-hoc tests showed that both the repetition priming effect and the TR priming effect were significant (repetition priming: $z = 9.66$, $p < .001$; TR priming: $z = 5.21$, $p < .001$) but, as in Experiment 2, the repetition priming effect was stronger than the TR priming effect.

Error rates for the "same" trials. No main effect or interaction was significant, although there was a marginal effect of transposition ($\chi^2(1) = 3.70$, $p = .05$).

Latencies for the "different" trials. There was a significant main effect of prime-target relatedness ($\chi^2(1) = 13.98$, $p < .001$), however, the main effects of transposition and radical type were not significant (transposition: $\chi^2(1) = 0.97$, $p = .32$; radical type: $\chi^2(1) = 0.82$, $p = .37$). The responses were faster when the target was preceded by an unrelated prime than preceded by a related prime. There was no significant interaction.

Error rates for the "different" trials. No main effect or interaction was significant (all *p*s > .30).

2.3.2.2 ERP analyses

ERPs from 32 scalp channels time-locked to the onset of targets are plotted in Figure 14 (NCR characters, repetition priming), Figure 15 (CR characters, repetition priming), Figure 16 (NCR characters, TR priming) and Figure 17 (CR characters, TR priming).

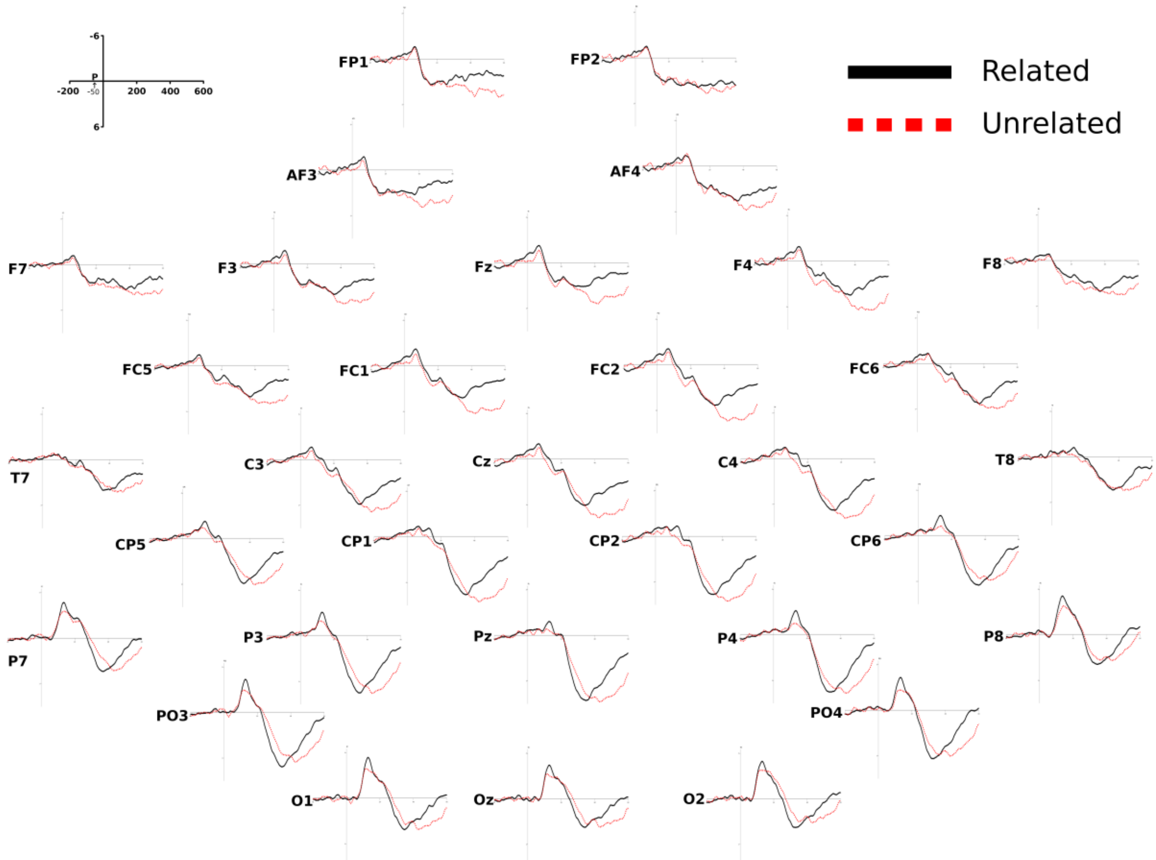

Figure 14: ERPs from all 32 scalp channels time-locked to the onset of NCR character targets in the repetition (black solid) and unrelated (red dotted) conditions in Experiment 3.

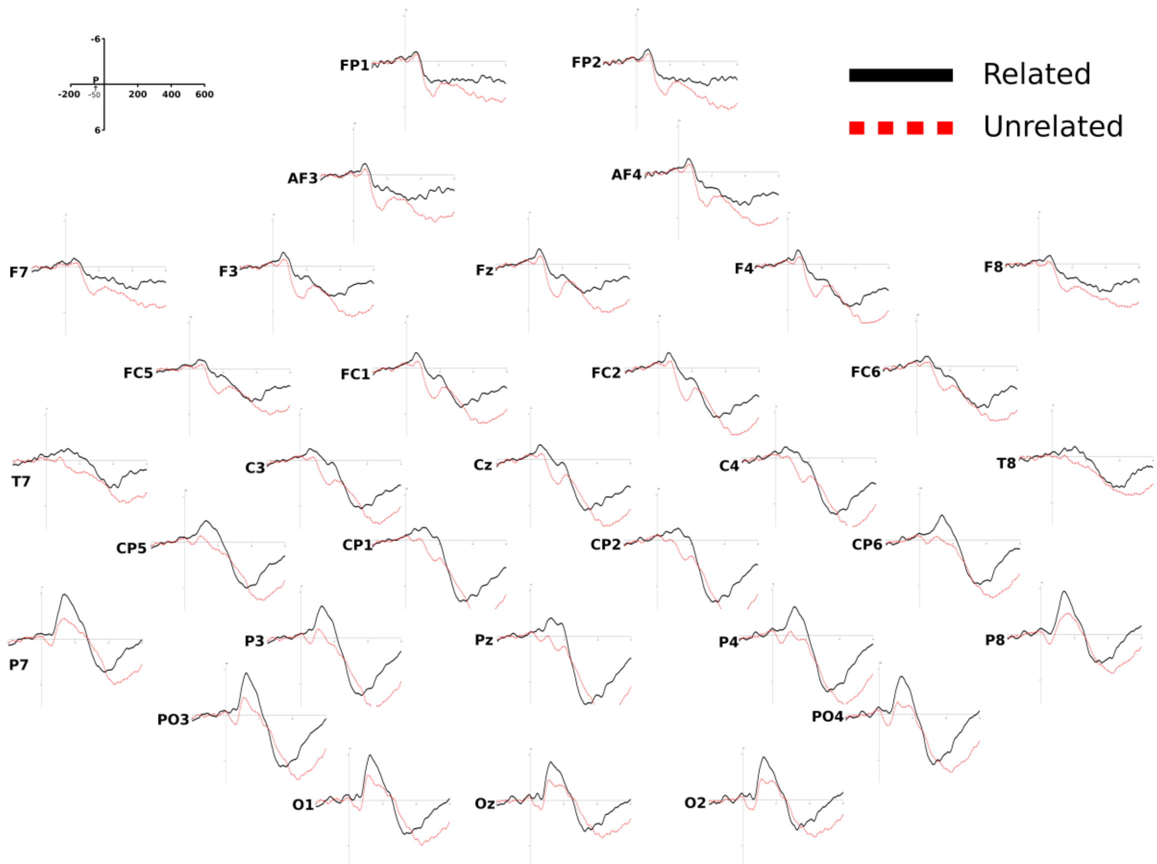

Figure 15: ERPs from all 32 scalp channels time-locked to the onset of CR character targets in the repetition (black solid) and unrelated (red dotted) conditions in Experiment 3.

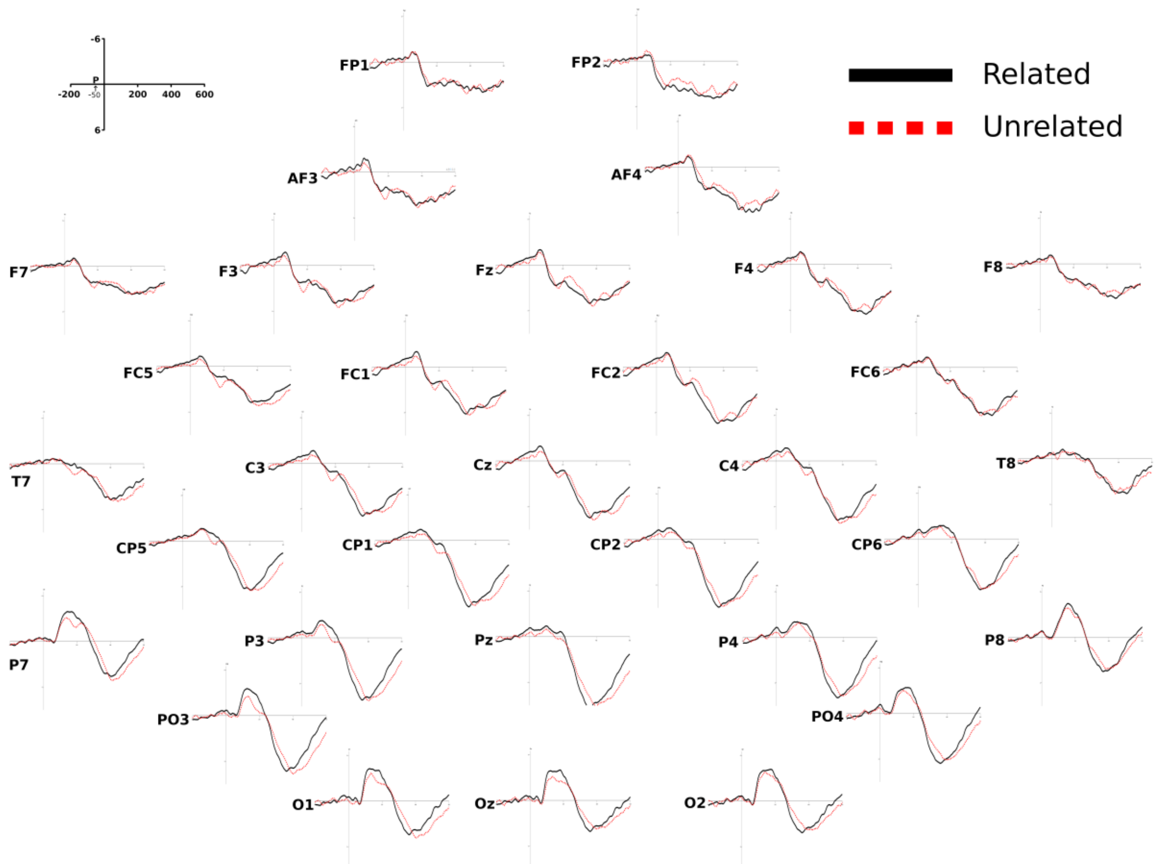

Figure 16 ERPs from: all 32 scalp channels time-locked to the onset of NCR character targets in the transposed (black solid) and unrelated (red dotted) conditions in Experiment 3.

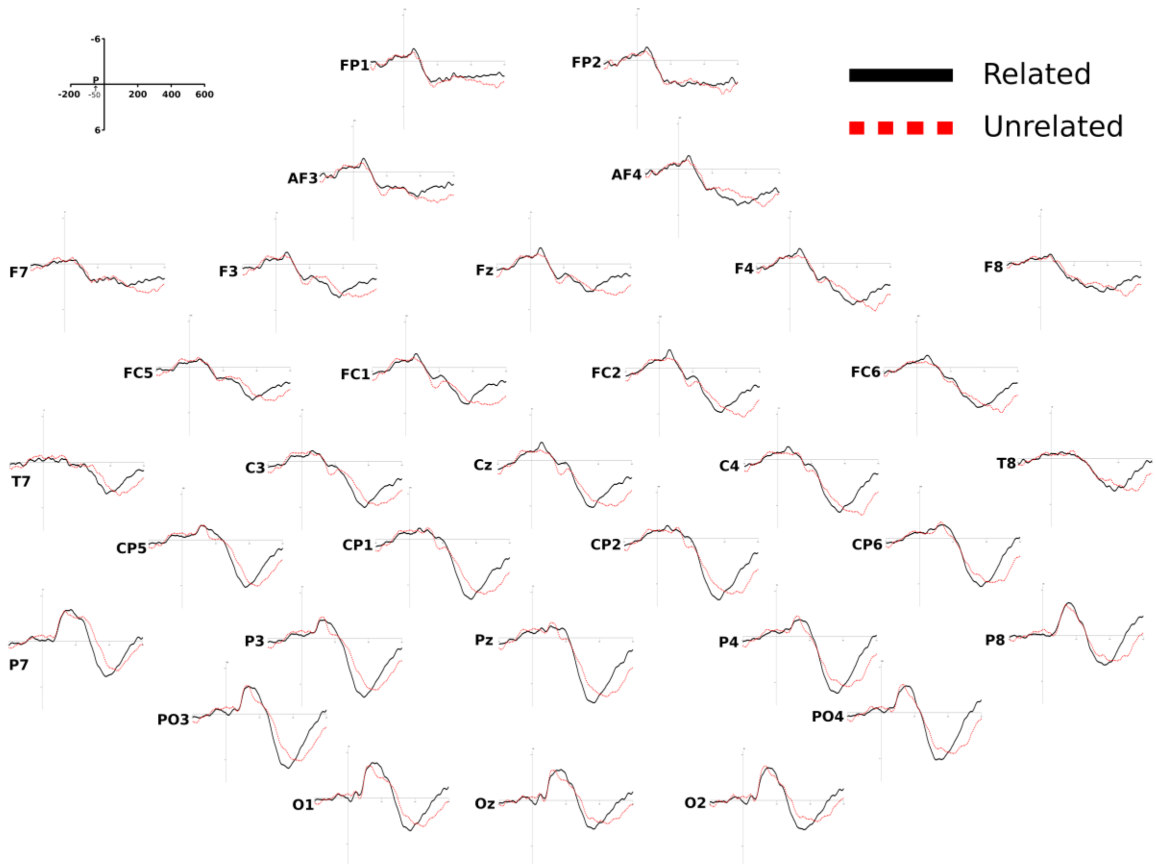

Figure 17: ERPs from all 32 scalp channels time-locked to the onset of CR character targets in the transposed (black solid) and unrelated (red dotted) conditions in Experiment 3.

From visual inspection of the repetition vs. unrelated waves of NCR characters (Figure 14), it can be seen that there was a negative going component both in the posterior area and especially in the occipital area around 130 ms after target onset (e.g., the O1 site, Figure 18A). This component was more negative for the related condition than the unrelated condition and this effect was less obvious or nonexistent in the TR data (Figure 19). Immediately after this negative component, there was a positive going component in the central area around 170 ms after target onset (e.g., the FC2 site, Figure 18B). This component was more positive for the unrelated condition than the related condition and visible in all four figures (Figure 20). Lastly, there was a widely distributed large positive component after 250 ms of target onset in all four figures (e.g., the Pz site, Figure 18C). This component showed up earlier for the related condition than the unrelated condition.

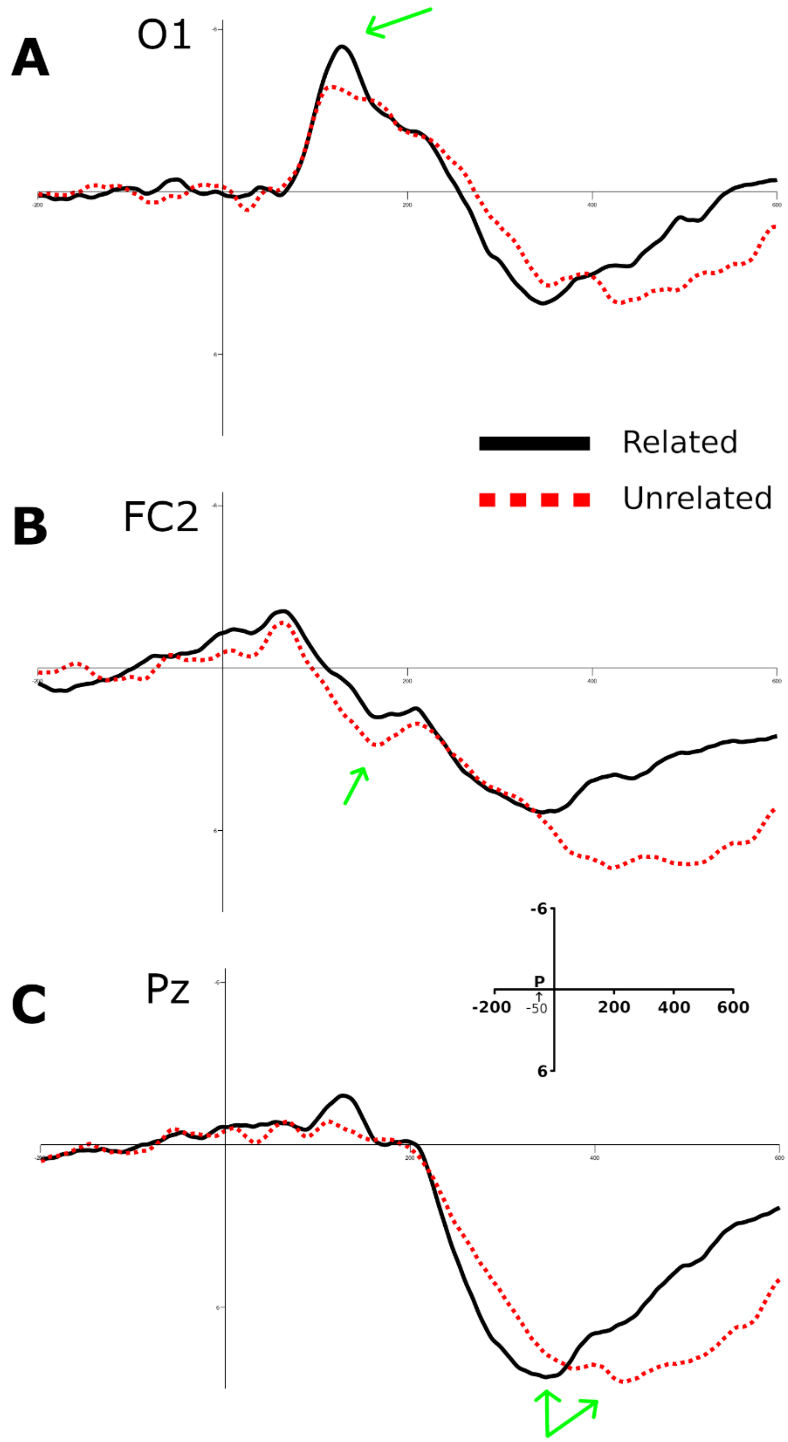

Figure 18: The O1, FC2, Pz sites from Figure 14. Each green arrow denotes a component.

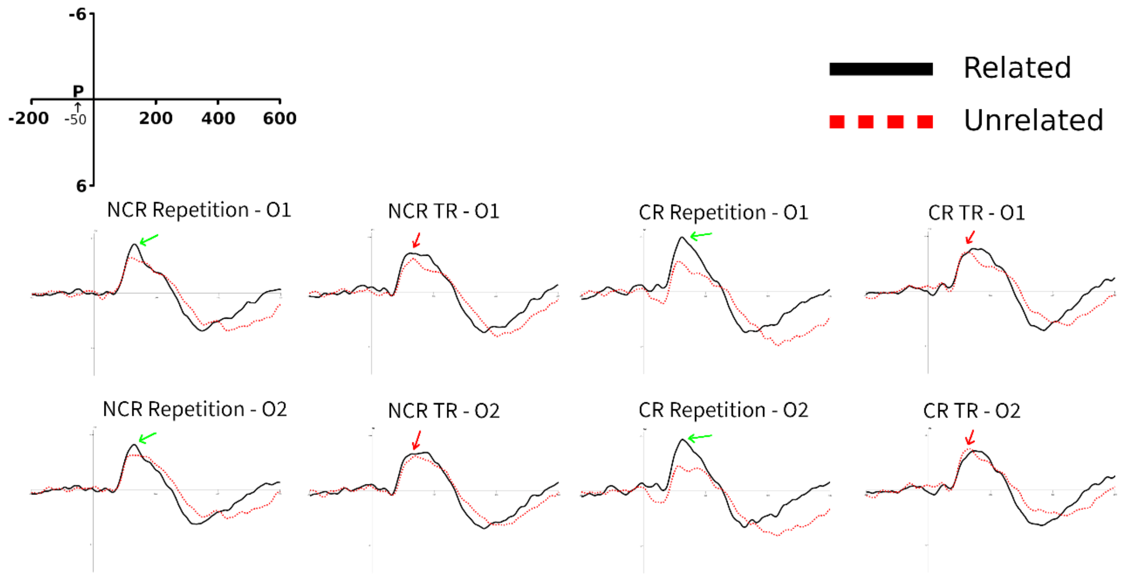

Figure 19: The early negative component in the occipital area around 130 ms in all four conditions in Experiment 3. This effect was less obvious for the TR condition (red arrows) than the repetition condition (green arrows).

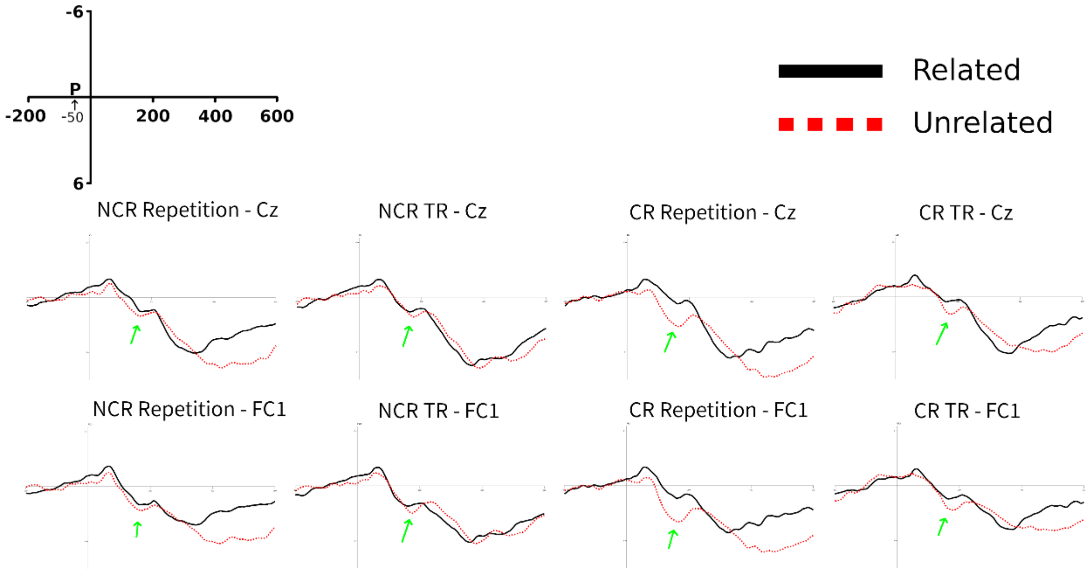

Figure 20: The positive component around 170 ms in all four conditions in Experiment 3.

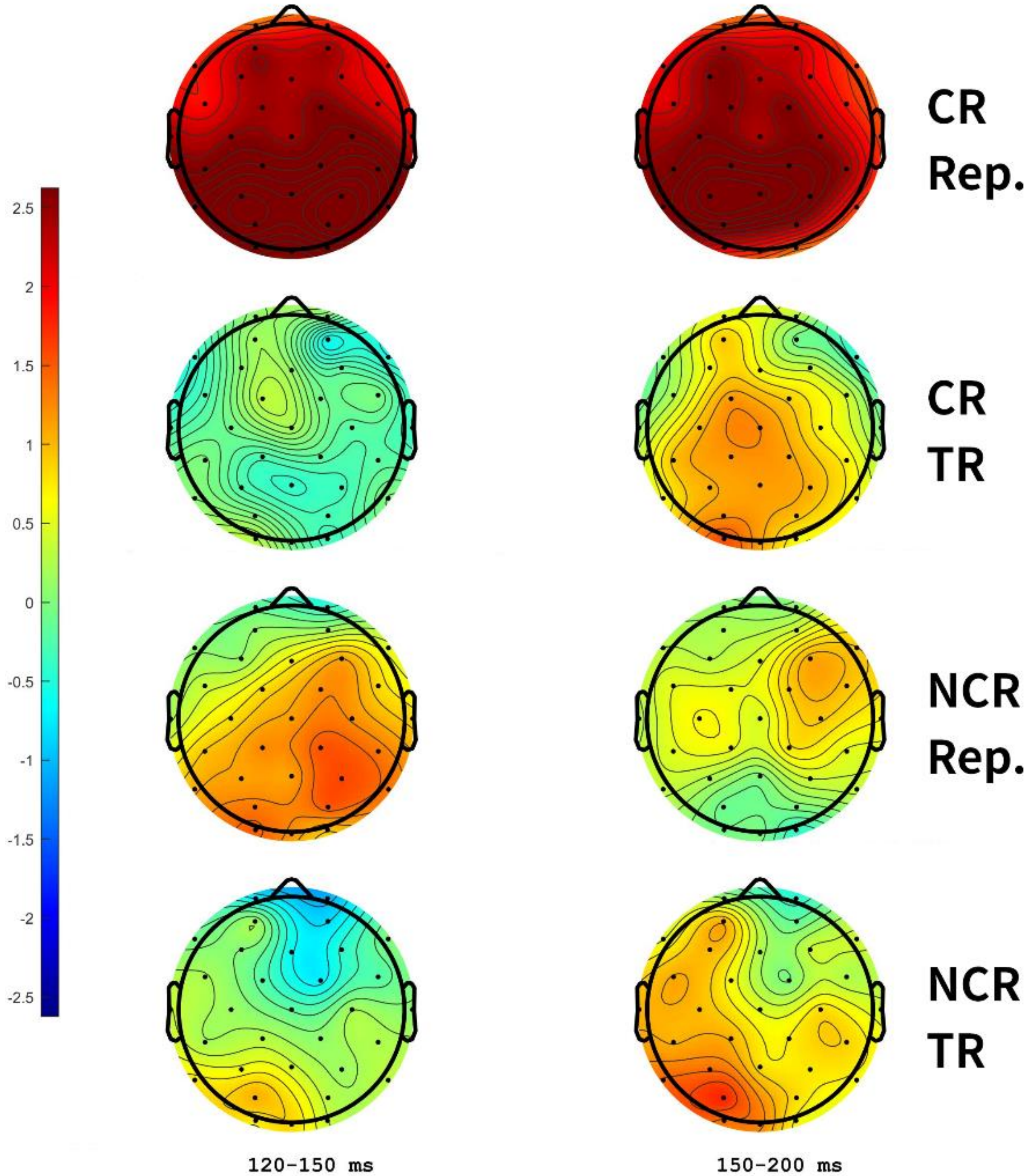

Figure 21: Scalp maps of the difference of the mean amplitude of waveforms between the unrelated and related conditions (unrelated – repetition/TR) from 120 to 200 ms for the NCR and CR character targets in Experiment 3.

Based on the results of previous studies and the visual inspections of the wave forms, three time windows were chosen: 120-150 ms, 150-200 ms, and 250-500 ms. The first time window was for the analysis of early positive going component in the occipital area. The second time window was for the analysis of the positive going component around 170 ms. The third time window was for the analysis of the large negative going component after 250 ms. Note that the mean amplitudes of wave forms were analysed in the first two time windows, while in the last one the peak latencies of the wave forms were analysed. In an effort to capture distributional effects in these data while minimizing the number of comparisons, the 32 head channels were grouped into three separate areas along the anteroposterior axis of the head (see Figure 22). The mean amplitudes (or the peak latencies for the analysis in the last time window in Experiment 3) in each of the three areas were analysed in separate ANOVAs.

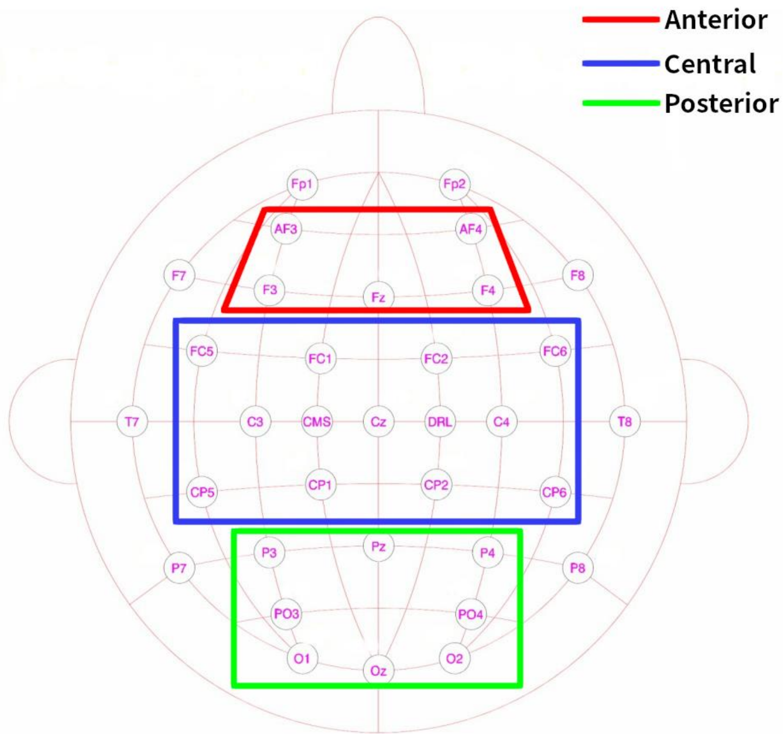

Figure 22: The three area groups of electrode sites used for the ANOVAs in Experiment 3.

120 to 150 ms target epoch. *For the repetition condition*: There was a main effect of Relatedness in all three areas [Anterior: $F(1, 31) = 8.67$, $p = .006$; Central: $F(1, 31) = 15.33$, $p < .001$; Posterior: $F(1, 31) = 23.81$, $p < .001$]. The two way interaction of Relatedness × Radical Type was significant in all three areas [Anterior: $F(1, 31) = 6.81$, $p = .014$; Central: $F(1, 31) = 8.27$, $p = .007$; Posterior: $F(1, 31) = 12.47$, $p < .001$]. The post-hoc analyses showed that while the repetition condition elicited more negative waves, the effect was larger for the CR characters than NCR characters in the central and posterior areas (Central-CR: $t = -4.10$, $p < .001$; Central-NCR: $t = -2.46$, $p = .020$; Posterior-CR: $t = -5.88$, $p < .001$; Posterior-NCR: $t = -2.34$, $p = .026$) and only significant for the CR character in the anterior area (Anterior-CR: $t = -3.33$, $p = .002$; Anterior-NCR: $t = -0.94$, $p = .35$).

For the transposed (TR) condition: There was no main effect of Relatedness or Radical Type (all *p*s > .15). None of the interactions were significant either (all *p*s > .30).

150 to 200 ms target epoch. *For the repetition condition*: There was a main effect of Relatedness in all three areas [Anterior: $F(1, 31) = 4.67$, $p = .038$; Central: $F(1, 31) = 8.78$, $p = .006$; Posterior: $F(1, 31) = 6.42$, $p = .017$]. The two way interaction of Relatedness × Radical Type was significant in all 3 areas [Anterior: $F(1, 31) = 5.72$, $p = .023$; Central: $F(1, 31) = 8.84$, $p = .006$; Posterior: $F(1, 31) = 13.32$, $p < .001$]. The post-hoc analyses showed that while the repetition condition elicited more negative waves, the effect was only significant for the CR characters in all three areas (Anterior-CR: $t = -2.61$, $p = .014$; Anterior-NCR: $t = -0.86$, $p = .40$; Central-CR: $t = -3.51$, $p = .001$; Central-NCR: $t = -1.32$, $p = .20$; Posterior-CR: $t = -4.17$, $p < .001$; Posterior-NCR: $t = -0.03$, $p = .98$).

For the transposed (TR) condition: There was a main effect of Relatedness in the central and posterior areas [Anterior: $F(1, 31) = 1.68$, $p = .20$; Central: $F(1, 31) = 5.97$, $p = .020$; Posterior: $F(1, 31) = 13.18$, $p = .001$]. The two-way interaction of Relatedness × Radical Type was not significant in any of the three areas (all *p*s > .80). The repetition condition elicited more negative waves in the central and posterior areas.

250 to 500 ms target epoch. *For the repetition condition*: There was a main effect of Relatedness in all three areas [Anterior: $F(1, 31) = 14.11$, $p < .001$; Central: $F(1, 31) = 17.64$, $p < .001$; Posterior: $F(1, 31) = 35.49$, $p < .001$]. The two-way interaction of Relatedness × Radical Type was not significant in any of the three areas (all *p*s > .50). The repetition condition elicited earlier wave peaks in all three areas.

For the transposed (TR) condition: There was a main effect of Relatedness in the central and posterior areas [Anterior: $F(1, 31) = 2.75$, $p = .11$; Central: $F(1, 31) = 13.79$, $p < .001$; Posterior: $F(1, 31) = 32.47$, $p < .001$]. The two-way interaction of Relatedness × Radical Type was significant in the anterior and central areas [Anterior: $F(1, 31) = 6.23$, $p = .018$; Central: $F(1, 31) = 5.62$, $p = .024$; Posterior: $F(1, 31) = 0.90$, $p = .35$]. The post-hoc analyses showed that while the repetition condition elicited earlier wave peaks in all three areas, the effect was only significant for the CR characters in the anterior and central areas (Anterior-CR: $t = -2.57$, $p = .015$; Anterior-NCR: $t = 0.17$, $p = .87$; Central-CR: $t = -3.85$, $p < .001$; Central-NCR: $t = -1.28$, $p = .21$).

2.3.3 Discussion

In Experiment 3, a significant main effect of relatedness and a significant interaction between relatedness and transposition was found, just as in Experiment 2. The critical finding was that the responses were faster in the TR condition than the unrelated condition. This TR priming effect here confirms the reality of the TR priming effect found in Experiment 2. Since the masked priming same-different matching task is argued to be based mainly on activity at the orthographic level, the finding of a TR effect in this task suggests it is an effect of orthographic processing in both tasks, which further suggests that the orthographic coding of radical position is not specific. As in Experiment 2, the fact that radical type didn't interact with the TR effect indicates that the radical type information doesn't play a role in the orthographic processing of radicals. The results from different trials that there was no interaction involving radical type also support this conclusion.

The ERP data were consistent with the behavioural data. The results of the ANOVA analyses are summarised in Table 5. The results showed that the main effects of Relatedness and the interactions involving Relatedness were obtained across all three time windows for repetition, but only showed up in the later two time windows for TR. To summarise the ERP results in detail, three components were identified: an early negative component around 130 ms, a positive going component around 170 ms, and a large positive component after 250 ms. Note that the identified components were not the same as in Experiment 2, probably due to the task change. The first negative component, the N/P150, which is hypothesized to reflect the mapping of visual features onto letter identities, or radical identities in the case of this experiment, was found to be modulated by repetition priming but not by TR priming. This pattern was quite similar to that observed in Experiment 2. The second component was more positive in the unrelated condition. The wave peak of the third component was later for the unrelated condition.

Indeed, Norris et al. (2018) also found that a peak latency effect arose when using a masked priming same-different matching task – "whereby the ERPs for identity primed trials are shifted earlier in time relative to those for unprimed control trials" (p. 1158). What's more important, the second and last components were both modulated by the repetition and TR priming and the patterns of repetition and TR priming were the same. This pattern suggests that the repetition and TR priming effects found in the behavioural data had the same origin as early as 170 ms after target onset, which can reasonably be assumed to have arisen at the orthographic stage.

Table 5: ERP ANOVA results of Experiment 3. Each asterisk in the table indicates a significant (*p* < .05) main effect or interaction.

Time Window	Area	Repetition			TR		
		Relatedness	Rad_Type	Relatedness × Rad_Type	Relatedness	Rad_Type	Relatedness × Rad_Type
Window 1 120-150 ms	Anterior	*		*			
	Central	*		*			
	Posterior	*		*			
Window 2 150-200 ms	Anterior	*		*			
	Central	*		*	*		
	Posterior	*		*	*		
Window 3 250-500 ms	Anterior	*					*
	Central	*			*		*
	Posterior	*			*		

In terms of the radical type, the ERP results showed that there were more obvious effects for CR characters than NCR characters in all three time windows. This seems to suggest that CR characters can generate larger TR effects, which indeed is what was expected. However, it was only in the last time window that there was a radical type difference in the TR condition (as the Electrode Site factor × Relatedness × Radical Type interaction in Column 2 showed), while in the first two time windows the difference was only in the repetition condition. Therefore, there is still little evidence that radical type has an impact on the TR effect.

Findings in this experiment will have impact on theories of Chinese character orthographic processing, since most current models assume that the radical positions are coded precisely. In Experiment 1, the simulations used the same functional architecture and algorithms that have been applied to English models to simulate TL effects, suggesting that parallel mechanisms may be underlying any TL like effects in the two different languages and writing systems (e.g., Chinese and English). Therefore, our further findings of TR effects in Chinese would also have an impact on the more general theories of visual word recognition.

As noted, there are two types of models that try to explain TL-type effects in word recognition, one can be called the noisy position coding models and the other is open bigram models. The latter of these would not seem capable of explaining any TR priming effects observed here. That is, the Chinese characters used in Experiment 2 and 3 are all left-right structure characters and each can only be decomposed into two radicals/components. Thus, there are no open bigrams at play here. Even if there were something like an open bigram level for radicals, there would only be one open radical bigram activated by a character, that open bigram would be completely different for a character and its TR correspondence (e.g., a character consisting of two radicals A and B would activate the representation for open bigram A-B, and its TR correspondence would activate the representation for open bigram B-A). Therefore, TR priming effects could not be explained within the framework of the open-bigram models.

2.4 Experiment 4

In previous studies of TR effects in Chinese, the stimuli often contained characters with different structures, which may have been problematic. In their Experiment 3, Ding et al. (2004) didn't mix different structure characters but allowed shape and size changing of radicals and only found a non-significant 11 ms TR priming effect. In our Experiments 2 and 3, I only used left-right structure characters and retained the shape and size of radicals. In doing so, TR priming effects were consistently found. These results support the idea that the size and shape changing of radicals was a problem in previous studies. If the other potential confound, structure mixture, was also a problem, different results may be found when using characters with a structure other than left-right.

In Experiment 4, this issue was investigated by using the same task as in Experiment 3 (i.e., the masked priming same-different task), and characters with the second most common structure, the top-bottom structure, as stimuli. By comparing the results of Experiments 3 and 4, it can be determined whether the positional coding for radicals is the same for characters using these two different character structures.

2.4.1 Method

Participants. Forty adults (mean age: 34.8) from Zhonghuayuan Elementary School, Kunshan, Jiangsu, China participated in the experiment. All of them are right-handed native Mandarin Chinese speakers with normal or corrected-to-normal visual acuity.

Materials. One hundred twelve top-bottom structure Chinese characters consisting of two radicals were chosen to be the targets and reference stimuli on the “same” trials. Fifty-six of them contain 2 CRs and the other 56 characters contain at least 1 NCR. Unlike in Experiments 2 and 3, however, these characters were not all made by two free radicals because almost all top-bottom CR characters involve two free radicals, while most NCR top-bottom characters involve at least one bound radical. In addition, the ratio of the sizes of two radicals in a top-bottom character is also related to its radical type. The top-bottom CR characters usually have radicals that are closer in size than NCR radicals. The potential impact of this difference will be discussed subsequently. The CR characters and NCR characters were matched in terms of radical stroke numbers (4.8 and 4.3 vs. 4.0 and 4.6) and frequency (128.0 vs. 201.4 /million characters, according to SUBTLEX-CH database, Cai & Brysbaert, 2010). Another 224 characters were chosen as the reference and target stimuli for the “different” trials (112 characters for each role). Targets on "same" and "different" trials and reference stimuli on "different" trials were matched on frequency (same: 164.70, different: 168.45, reference: 159.48, $F(2, 333) = 0.015$, $p = .99$) and stroke number (same: 8.89, different: 9.31, reference: 9.57, $F(2, 333) = 1.85$, $p = .16$). However, due to the limited number of top bottom characters, these 224 characters were not matched to the materials in the "same" trials in terms of the radical type (i.e., the CR and NCR characters were mixed in the different trials and not controlled). Two hundred and twenty-four TR primes were created by transposing the two radicals in the target characters in the same way as in Experiments 2 and 3. They are all non-characters. The unrelated primes were again created by re-pairing the related primes. The 4 prime types were the same as in Experiments 2 and 3 as was the list construction for the "same' trials. On the "different" trials, as in Experiment 3, a "zero contingency" scenario was used.

Procedure. Experiment 4 used the masked priming same-different matching task. The procedure was the same as in Experiment 3 except that EEG data were not collected due to there not being the necessary equipment at the experimental site. DMDX software was used to program the experiment and collect behavioural reaction time and accuracy data.

2.4.2 Results

The average error rate was 2.5% across participants and there was no item with a high error rate. Latencies for incorrect responses were excluded from the latency analyses, as were latencies that were shorter than 200 ms or longer than 2000 ms (2.6% of all data). The latencies from the correct trials and the error rates for the "same" trials were analysed using GLMMs. The mean response latencies (in milliseconds) and percentage error rates are shown in Table 6. The data for the different trials are also shown. Note that the materials in the "different" trials were only matched to the CR and NCR characters in terms of frequency and stroke number, not radical type.

Table 6: Mean response latencies (reaction times [RTs], in milliseconds) and percentage error rates (in parentheses) in Experiment 4.

		CR characters				NCR characters			
		Repetition		Transposed		Repetition		Transposed	
Same	Related	581	(1.07)	607	(2.86)	593	(2.15)	590	(1.43)
	Unrelated	624	(3.76)	605	(3.94)	627	(4.65)	622	(3.40)
	Priming	*43*	*(2.69)*	*-2*	*(1.08)*	*34*	*(2.50)*	*32*	*(1.97)*
Diff	Related	657	(2.33)	642	(2.14)	650	(1.96)	635	(3.04)
	Unrelated	627	(1.25)	635	(1.07)	621	(2.33)	634	(2.50)
	Priming	*-30*	*(-2.08)*	*-7*	*(-1.07)*	*-29*	*(0.37)*	*-1*	*(-0.54)*

The latencies and error rates were analysed using GLMMs with the same method and packages as in Experiments 2 and 3. The models used to fit the GLMMs were also the same as in Experiments 2 and 3, since the fixed and random effect factors are the same in the two experiments. To fit GLMMs for the latency analyses, the Gamma distribution was used with an identity link between fixed effects and the dependent variable. The model for the latency analysis of the same trials was: RT ~ Relatedness * Transposition * Radical_Type + (1 | Subject) + (1 | Item). Because the materials in the “different” trials were not controlled for radical type, the model for the latency analysis of the “different” trials was: RT ~ Relatedness * Transposition + (1 | Subject) + (1 | Item). To fit GLMMs for the error rate analyses, the binomial distribution with the logistic link function was used. The model for the error rate analysis of the “same” trials was: ACC ~ Relatedness * Transposition * Radical_Type + (1 | Subject) + (1 | Item). The model for the error rate analysis of the “different” trials was: ACC ~ Relatedness * Transposition + (1 | Subject) + (1 | Item)

Latencies for the “same” trials. There was a significant main effect of Relatedness ($\chi^2(1) = 51.38$, $p < .001$). The main effects of Transposition and Radical type were not significant (transposition: $\chi^2(1) = 0.22$, $p = .64$; radical type: $\chi^2(1) = 0.51$, $p = .48$). Responses were faster when the target was preceded by a related prime than when preceded by an unrelated prime. There were two significant interactions, the interaction between Relatedness and Transposition ($\chi^2(1) = 12.97$, $p < .001$) and the three-way interaction of Relatedness, Transposition, and Radical type ($\chi^2(1) = 9.51$, $p = .002$). Post-hoc tests showed that the repetition priming effect was significant for both CR and NCR characters (CR: $z = 6.44$, $p < .001$; NCR: $z = 4.25$, $p < .001$) but the TR effect was only significant for NCR characters (NCR: $z = 3.73$, $p < .001$; CR: $z = 0.31$, $p = .76$).

Error rates for the "same" trials. There was a significant main effect of Relatedness ($\chi^2(1) = 17.47$, $p < .001$). The related condition elicited more accurate responses than the unrelated condition. There was also a significant interaction between Transposition and Radical type ($\chi^2(1) = 5.18$, $p = .020$), however, post-hoc tests showed that the difference between the transposed and repetition conditions were not significant for either the CR or NCR character (CR: $z = 1.84$, $p = .07$; NCR: $z = 1.37$, $p = .17$).

Latencies for the "different" trials. There was a significant main effect of Relatedness ($\chi^2(1) = 21.99$, $p < .001$). The main effect of Transposition was not significant ($\chi^2(1) = 1.10$, $p = .29$). Responses were faster when the target was preceded by an unrelated prime than when preceded by a related prime. The interaction between Relatedness and Transposition was significant ($\chi^2(1) = 9.58$, $p = .002$). Post-hoc tests showed that the difference between the related and unrelated conditions was significant for the repetition condition ($z = 5.47$, $p < .001$) but not significant for the transposed condition ($z = 1.14$, $p = .26$).

Error rates for the "different" trials. Neither of the main effects of Relatedness ($\chi^2(1) = 1.82$, $p = .18$) nor Transposition ($\chi^2(1) = 0.24$, $p = .62$) was significant. The interaction between Relatedness and Transposition was also not significant ($\chi^2(1) = 0.21$, $p = .65$).

2.4.3 Discussion

The left-right structure is the most common character structures used in Chinese and in studies using Chinese stimuli. Previous studies mostly focused only on compound characters with this structure (e.g., Ding et al., 2004; Hsiao, 2011; Chen & Yeh, 2017). However, there were studies that didn't take structure into consideration and used characters with different structures without the necessary counterbalancing (most of the stimuli were left-right with a few top-bottom exceptions, e.g., Taft et al., 1999; Su et al., 2012).

As noted, there is evidence that the character structure does play an important role in the perception of similarity of Chinese characters (Yeh & Li, 2002). Besides perception of similarity, the character structure also affects the expression of at least one effect, the regularity effect in Chinese experiments (Cai et al., 2012). Most Chinese compound characters have a semantic and a phonetic radical. The phonetic radical can provide phonological information about the pronunciation of the character. If a compound character has the same pronunciation as its phonetic radical, then it is called regular. The regularity effect refers to the phenomenon that the naming of regular characters is faster than that of irregular characters, which has been taken as evidence to support sub-character (i.e., radical) activation when reading Chinese characters and has been used to examine the cognitive plausibility of computational models (e.g., Plaut et al., 1996).

Cai et al. (2012) investigated the regularity effect and its interaction with character frequency and phonetic radical position in the left-right structure and top-bottom structure characters. They found that, for low frequency left-right structure characters, the radical position altered the direction of the regularity effect. The left-right characters with a phonetic radical on the right side showed a regularity effect, while a reversed regularity effect was found when the phonetic radical was on the left. In contrast, the direction of the regularity effect was not altered in the low frequency top-bottom structure characters (there was always a regularity effect). This result suggests that characters with different structures may be processed in slightly different ways in the reading of Chinese characters. Therefore, the results in cognitive experiments in which different structure characters stimuli were mixed, particularly without counterbalancing them across conditions could have been compromised.

The critical result of Experiment 4 was the significant interaction between Relatedness, Transposition, and Radical type in the “same” trials. For the repetition priming effect, the radical type didn't have an impact, because the CR and NCR characters showed similar size priming effects. For the TR priming effect, however, different from the results of Experiments 2 and 3, only the NCR characters elicited a significant TR effect. This result is also contrary to our expectation that, if there is any radical type difference, the CR characters should show a larger TR effect than the NCR characters, because a CR is a character by itself, unlike an NCR which can only exist in a character in combination with another radical. Therefore, the expectation is that position information is likely to be more important for an NCR than a CR.

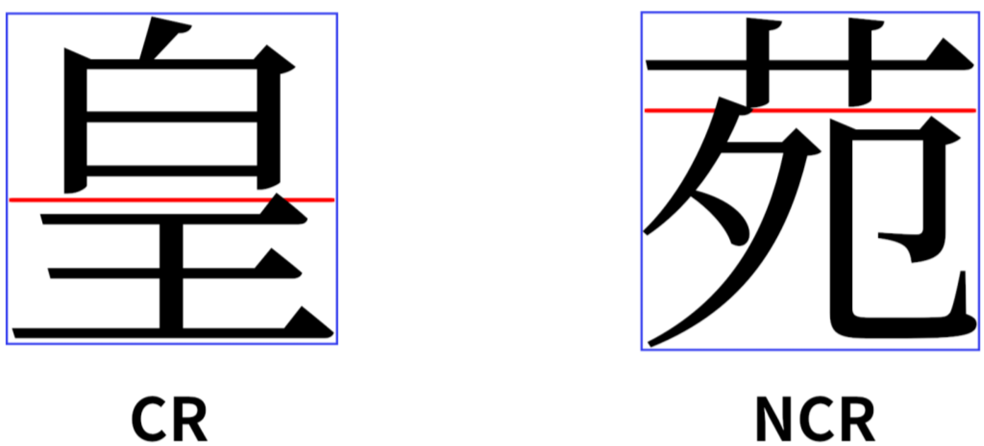

Figure 23: Examples of top-bottom structure character. The blue squares indicate the space a character takes, the red lines separate the two radicals in a character.

Given that in Experiments 2 and 3 there were no CR/NCR differences, it is reasonable to ask whether this difference in TR effects in Experiment 4 could have been caused by a confound. Radical size difference is such a potential confound. For top-bottom CR characters the two radicals are more similar in size than for NCR characters (Figure 23). In order to evaluate this issue here, the images of targets for the same trials were divided into two parts with a horizontal line, one containing the top and the other containing the bottom radical. Then the ratio of the size of the larger radical to the smaller radical for all these targets was calculated. As expected, the ratios were significantly different between

CR and NCR characters. The mean ratios of CR and NCR characters were 1.36 and 2.19, respectively ($t(110) = 7.97$, $p < .001$).

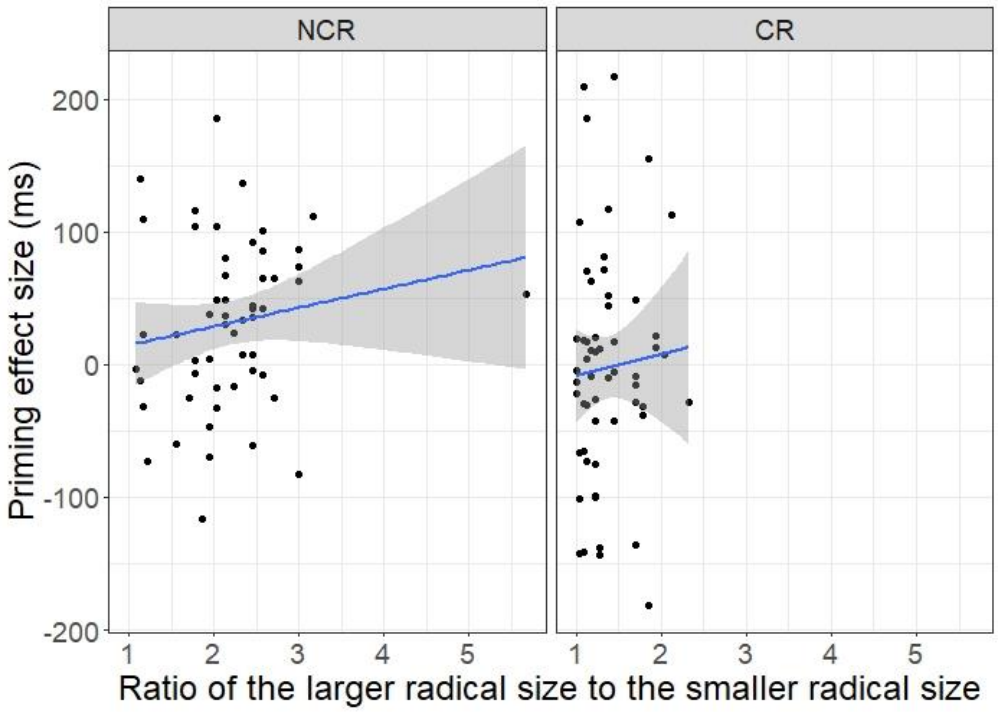

Figure 24: The relationship between the radical ratio and the TR priming effect size for the response time on the same trials. The blue line is the linear regression line and the shadow represents the standard errors.

Essentially, the larger radical is more than two times larger than the smaller radical in top-bottom NCR characters on average. Therefore, even after being switched with the smaller radical, the larger radical is only moved up or down a small distance and still occupies the majority of the character square. As a result, it would seem that the TR non-character primes would be more likely to activate the target character based on the simple existence of the large radical with the smaller radical being quite difficult to see. That is, the TR effect observed for the NCR characters is likely a single radical priming effect. As a reference, the means of radical ratios of the targets for "same” trials in Experiment 2 and 3 were also calculated, and they were not significantly different between CR (1.35) and NCR (1.44) characters ($t(118) = 1.87$, $p = .064$). When the relationship between the radical ratio and the TR priming effect size on the same trials was examined, the results showed that the correlation was small ($r = 0.06$, $p = .65$) for the CR characters and was $r = 0.16$ ($p = .24$) for the NCR characters, as shown in Figure 24. The nonsignificant correlation between the priming effect and the ratio for NCR characters suggested that the radical ratio may not fully explain the priming effect for NCR characters in Experiment 4.

In any case, even if the radical ratio does not account for the difference between Experiment 4 and the two previous experiments, it is important to note that a different pattern of results was observed in Experiment 4. Radical type mattered in terms of producing a TR effect. The impact of radical type has been much overlooked in previous studies and it needs further investigation to find out why radical type interacts with the TR effect for the top-bottom structure characters, but not for the left-right structure characters. Empirically, what needs to be noted is that mixing characters of different structures in the materials could be a reason why previous studies didn't find any TR effect.

Note that due to COVID-19 restrictions I was unable to collect the data of Experiment 4 at Western University where the data of Experiments 2 and 3 were collected. Instead, I collected the data in a school in China where the COVID restrictions were less severe at that time. Our participants in Experiment 4 were all elementary school teachers who were older than our participants in Experiments 2 and 3 and, hence, had been reading Chinese script for a longer period of time. However, there is no reason to suspect that the demographic difference of participants is responsible for the different result pattern in Experiment 4. The participants in Experiments 2 and 3 were all native Chinese speakers who had just arrived at Canada, having been in Canada less than 1 year. Based on the behavioural data, they performed quite well in processing Chinese targets, even responding slightly faster to the targets, on average, than the participants in Experiment 4. Another property of the participants in Experiment 2 and 3 that may differ from the participants in Experiment 4 is that they were all able to speak English with a certain level of fluency. In order to make sure their L2 was activated as minimally as possible, I created a monolingual experiment environment with only Chinese instructions and conversations.

Chapter 3: General Discussion

Successful reading requires the reader to retrieve phonological and semantic information based on the orthographic inputs available. In order to do so, the code derived from the orthographic inputs needs to be reasonably accurate. Therefore, one of the most important research topics in this research area is how component position information is represented during reading.

The finding of TL effects is an interesting milestone in this body of research (e.g., Perea & Lupker, 2003). TL effects imply that a TL nonword (e.g., jugde) is perceived and treated as more similar to its base word (e.g., judge) than the parallel SL nonword (e.g., jupfe). This fact is incompatible with the classic slot coding models (e.g., the Interactive Activation model: McClelland & Rumelhart, 1981, Rumelhart & McClelland, 1982; the Multiple Read-Out model: Grainger & Jacobs, 1996; the Dual Route Cascaded model: Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; the Bayesian Reader model: Norris, 2006, 2009) in which letter position information is assumed to be rapidly and accurately coded. Subsequently, a number of models have been proposed to explain this phenomenon. One type of model can be categorized as noisy position coding models (e.g., the Spatial Coding model: Davis, 2010; the Overlap model: Gomez et al., 2008; the Noisy Channel Bayesian Reader model: Norris et al., 2010) as they all assume that, at the early stages of processing, the letter position is coded in a fuzzy and flexible fashion. Another type of model assumes that there is an intermediate level of representation, bigram representations, between the letter level and the word level that produces TL effects (e.g., Grainger & van Heuven, 2004; Whitney, 2001).

The noisy position coding and open-bigram models don't postulate any language specific assumptions and therefore, should be applicable to all languages. However, the extensive research on TL effect in different languages has shown that the TL effect is absent in some languages, particularly Hebrew (Velan & Frost, 2009) and Korean (Lee & Taft, 2009, 2011; Rastle et al., 2019). These types of results indicate that the TL effect is not universal and undermine the applicability of both noisy position coding and open-bigram models.

Even within the same language, the TL effect sometimes is modulated by word type. For example, Velan and Frost (2011) reported that the morphologically simple words in Hebrew (non-root-derived words) do show typical TL effects. Another example is found in Experiment 2 of Rastle et al. (2019), in which the lexical decision latency to three-letter monosyllable English target words was not affected by the presentation of a TL prime. Frost (2012) therefore argues that letter position coding flexibility is a function of certain aspects of a language, instead of a universal property of orthographic processing. He argues that the orthographic density of a language is such an aspect. For languages like English and French in which there are only a small portion of words that are anagrams, the orthographic density is low, and the precise coding of letter positions is not necessary in order to maximize the efficiency of accessing semantic information. For languages like Hebrew and Korean, however, in which a substantial number of words are anagrams, the precise coding of letter positions is vital for efficient semantic access.

For Korean Hangul, however, the situation may be more complex, because of one unique feature of it, that the Hangul syllable is arranged in a top-to-bottom configuration and syllables have physical separations. Lee and Taft (2009, 2011) suggested that this special feature makes it possible to code the positions of Hangul letters precisely, thus preventing a TL effect. In Chinese, the second most common character structure, the top-bottom structure, resembles this special visuospatial feature of Hangul syllables and might imply that the character structure could have an impact on the orthographic processing in Chinese character recognition.

In terms of the TL type effects, because Chinese, the language investigated here, is even more orthographically sparse (i.e., in terms of the number of anagrams) than French and English, it should allow the existence of TL type effects according to Frost’s (2012) hypothesis. At the level of characters, a transposed character (TC) effect has been reported (Yang et al., 2019) and this effect was further demonstrated to arise at the orthographic processing level (Yang et al., 2020). When considering radicals, I found that only 1.3% of 6500 common characters have counterpart anagrams (characters that have the same constituent radicals, regardless of structure). This fact suggests that, according to Frost's (2012) theory, there should be some degree of flexibility of radical position coding and, therefore, there should be a TL type effect at the radical level (a TR effect). Further, according to the noisy position coding models, the flexibility or uncertainty at the early stage of orthographic processing should be universal and applicable to Chinese. Therefore, those models also predict a TR effect in Chinese character recognition. In terms of the bigram models, they can predict transposed character effects for longer Chinese words but would have no means of doing so for shorter words (i.e., two-character words) or predicting TR effects.

To this point, no clear evidence of TR effects had been reported in empirical studies. Instead, many studies reported results supporting a "position-specific view" of radical representation (e.g., Taft, 2006; Perfetti et al., 2005). This view assumes that a radical has different orthographic representations when it is in different positions, and a radical can only activate the character representations containing that radical in that position. Certainly, there is some evidence supporting the "position-general view" of radical representation (e.g., Tsang & Chen, 2009), the view that doesn't assume different representations for the same radical in different positions. Further, there are also several caveats concerning the soundness of the previous studies showing no TR effect: (1) explicit (i.e., clearly visible) presentation of all stimuli which may easily allow post-orthographic coding effects; (2) appearance changes of radicals in different positions; (3) the mixed use of characters with different structures. These factors may have affected the results in behavioural studies and biased them toward supporting the position-specific view. Our experiments, therefore, were aimed at directly investigating the existence of TR effects in Chinese character recognition while trying to exclude those potential confounds.

3.1 Summary of the Present Findings

In Experiment 1, the question of whether position-specific models could predict a TR effect was addressed with computer simulations. Three networks with a simple structure and the same learning rules were trained to learn character pronunciations from orthographic inputs of characters. The first network (M1) was trained with orthographic inputs based on the position-specific view (i.e., radical identity and position information were coupled together, meaning that there were different representations for the same radical in different positions). The second and third networks (M2 and M3) were trained with orthographic inputs based on the position-general view (i.e., radical identity and position information were not coupled together, therefore, there was only one representation for a radical regardless of its position). The inputs for M3 had less reliable (i.e., scaled down) position information than those in M2. After feeding the trained networks with the inputs generated from the base characters, the correlations between the outputs of those base characters and those of both TR non-characters and unrelated non-characters across all materials were calculated. The higher the correlations with the output generated by the base character, the more similar the system finds the TR and unrelated non-characters to their base character. The simulated TR effect was calculated by subtracting the correlation score between outputs based on base and unrelated inputs from the correlation score between outputs based on base and TR inputs. The larger the difference, the larger the similarity would be between the TR non-character and the base character than the similarity between the unrelated non-character and the base character. The results showed that M1 produced no simulated TR effect, but M2 and M3 were able to produce large effects.

Separately examining the two-radical left-right structure characters and two-radical top-bottom structure characters, it was found that the two types of characters produced similar sizes of simulated TR effects. Because the inputs simply contain the codings for different types of structure but do not actually describe the visuospatial properties of characters with different structures, it is not surprising to find that there is no difference in simulated TR effects between the two structures. The question of whether there actually is a difference in real world settings was addressed in Experiments 2, 3 and 4.

In Experiments 2, 3 and 4, I used the masked priming technique to try to tap into the orthographic processing stage. Because the subliminal primes are displayed so briefly in the masked priming paradigm it's unlikely participants can form any prime-based strategy in that task. All non-character prime stimuli were created by switching the two radicals in a character without changing their shapes or sizes. Experiments 2 and 3 involved only the left-right structure characters, while Experiment 4 involved only the top-bottom structure characters. Therefore, the three potential problems in the aforementioned studies were minimized in our experiments. In addition, EEG data were also recorded in Experiments 2 and 3 to help us analyse the origin of the effects with a more fine-grained temporal resolution. I also examined whether the TR effect would be different for two radical types (i.e., character radical characters vs. non-character radical characters). Since a CR is a character by itself and an NCR can only exist in a character in combination with another radical, position information may be more important for an NCR than a CR. Therefore, if any TR effect is affected by the radical type, it's expected that the characters containing only CRs will show larger TR effects than the characters containing NCRs.

The behavioural results of Experiment 2 showed a robust repetition priming effect and a significant TR priming effect, both of which were not modulated by radical type (i.e., character or non-character radicals). Further, the ERP analysis showed that there was a repetition effect, but not a TR effect, in the first (earliest) component in the occipital area, one that appeared around 100 ms after target onset. This component would seem to be the N/P150 component that has been reported to be sensitive to visual features of the stimuli. Therefore, it is not surprising that a TR effect was not observed in this component because the primes and targets in the TR condition were not visually similar. However, there was essentially no TR effect in any time window in Experiment 2. Although the ERP results in Experiment 3 seem to indicate that the TR effect arises slightly later than the repetition effect the absence of a TR effects in the ERP data in Experiment 2 suggested that the situation was somewhat complicated. Specifically, there likely are procedures beyond orthographic processing producing the repetition effect. Indeed, the repetition primes share not only orthographic, but also phonological and semantic overlap with the targets, whereas the TR primes are only similar to the targets at the orthographic level. The lexical decision task is known to be affected by different types of priming effects (e.g., form, phonological, morphological and semantic priming). To minimize any potential priming effects based on these factors, a more orthographically oriented paradigm was used in Experiment 3.

The behavioural results of Experiment 3 replicated the results of Experiment 2 in virtually all ways. There was a robust repetition priming effect and a TR priming effect, and neither of them was modulated by the radical type. Since the masked priming same-different matching task is argued to almost entirely involve the orthographic level, these results suggest that the TR effect found in both tasks is an effect of orthographic processing. The ERP results were clear and consistent with the behavioural data. There was a repetition effect, but not a TR effect, in the first negative component which appeared around 130 ms after target onset. In the second positive component at around 170 ms and the third large positive component at around 250 ms, there were both repetition and TR effects. The fact that the second and last components were both modulated by repetition and TR priming, but the first N/P150 component was only modulated by the repetition priming, suggests that the TR priming effects found in the behavioural data originated in the orthographic level.

In Experiment 4, the question was whether characters with a different structure (top-bottom structure in this case) differ from the left-right characters used in Experiments 2 and 3 in terms of TR effects. The results showed that the TR effect, but not the repetition effect, was modulated by the radical type, with NCR characters but not CR characters producing a TR effect. It was also noted that there was a correlation between radical type and radical size ratio, with NCR characters having a larger radical size ratio. This correlation may work in favor of the NCR characters producing what appears to be a TR effect, although the correlation between the priming effect size and radical ratio for NCR characters was not significant. This leaves the challenge of providing a full explanation of why NCR characters showed an effect and CR characters didn't. Nevertheless, it doesn't change the conclusion that there was a different result pattern compared to Experiments 2 and 3. Therefore, it does appear that the top-bottom structure characters do differ from the left-right structure characters in terms of TR effects, supporting the idea that the character structure has an impact on the TR effect.

Note that the networks in Experiment 1 showed essentially equivalent simulated TR effects for the two types of structures. They also showed overly large effects compared to what were found in Experiments 2 and 3. Indeed, the models predicted simulated TR effects that were about 90% of the simulated repetition effect (which should involve a correlation of essentially 1.00). The failure of the models in these aspects would, however, seem to be understandable because of two reasons. Firstly, the networks in Experiment 1 are simplifications of the real reading situation in many ways and are unable to account for all the factors in reading. Secondly, the codings for character structure in orthographic inputs, as mentioned earlier, simply coded the types of character structure but did not actually describe the visuospatial properties of characters with different structures.

To summarise, Experiment 1 demonstrated that learning networks can show TL type effects if trained with orthographic inputs that follow the position-general view of radicals, but cannot show them if trained with inputs that follow the position-specific view. Experiments 2 and 3 showed that, using only the left-right structure characters and controlling the size and shape change of the radicals, a TR priming effect can be found in the lexical decision task and the same-different matching task. In the more orthographically oriented task (the masked priming same-different matching task) the ERP data showed that the TR effect emerged in a slightly later time window than the repetition priming effect, implying that the TR effect was produced at the orthographic processing stage, instead of the earlier feature processing stage or the later semantic processing stage. In Experiment 4, the TR effect was found to be modulated by radical type, which is a different pattern from the results of Experiments 2 and 3. In particular, there does not seem to be a TR priming effect for top-bottom characters and the pattern shown in Experiment 4 could be due to a confound of radical size ratio. Note that the finding in Experiment 4 of different TR effects for different radical types in the top-bottom structure characters not only may explain why some previous studies failed to get results that support the position-general view, but it also highlights the largely overlooked roles of character structure and radical type.

3.2 Theoretical Implications

The TR effect in the left-right characters can, in general, be explained by noisy position coding models. The previous models of Chinese character recognition that adopted the position-specific view should be modified to adopt the position-general view in order to explain the TR effect. That process will likely not be too difficult. For example, Taft's (2006) Multilevel Interactive-Activation framework can change its assumptions to allow a radical to send activation to all character representations that contain the radical, regardless of its position. It can also be assumed that the coding of the radical position has certain amount of noise in it, and the noise will become smaller with an increase in time of exposure to the stimulus. The TR effect found, however, doesn't seem to be compatible with the open-bigram models. Because all of the characters used in Experiments 2, 3 and 4 only contain two radicals, the bigram set of the TR prime would not have any similarity with the bigram set of the target character. The open-bigram models would need some fundamental modification to explain the TR effect. In terms of the impact of character structure, it is difficult for that impact to be explained by either the noisy position coding models or the open-bigram models, because these models were created to be a universal description of the TL effect and they cannot explain how to distinguish a certain set of characters/words from another set in one language. Nevertheless, there are several possible ways of explaining the different pattern in TR effects for left-right and top-bottom characters.

One possible explanation is that the system has a different processing method for the minority structures, which need finer position coding than the majority character structure (i.e., left-right structure). This explanation resembles the framework proposed by Grainger and Ziegler (2011), in which they proposed there are two different pathways of orthographic processing: the fine-grained analysis pathway (which performs detailed orthographic, morphemic, and phonological analysis of the visual input) and the rapid coarse-grained processing pathway (which provides rapid semantic access not relying on precise letter position). The recognition system balances the two pathways based on the task demands. If we apply the same assumptions to the recognition of characters with different structures, it can be postulated that the coarse-grained pathway largely takes care of the majority structure (left-right) and the fine-grained pathway largely takes care of the minority structures (e.g., top-bottom). However, the challenge for this explanation would be that there would seem to be no obvious way that the recognition system would be able to distinguish different types of characters (those with different structures) before they are processed and recognized.

Another possibility, consistent with Frost's (2012) theory, is that the precision of radical position representations is shaped by certain local statistical factors, and there are some differences in these factors between the top-bottom and the left-right structures. The idea would be similar to how the TL effect can be exist or not exist for different subsets of vocabulary in one language (Hebrew words without Semitic origin: Velan & Frost, 2011; English three-letter monosyllable words: Rastle et al., 2019). However, note that the simplified models M2 and M3 in Experiment 1 failed to pick up any difference between structures, basically showing the same size simulated TR effect for the two structures. This result is not consistent with Frost's theory and suggests that there are important factors that were not captured by the orthographic codes used in our simulations. The visuospatial feature of the stimuli can be such a factor and it leads to the next, seemingly more viable, possibility.

In Korean Hangul the syllables are demarcated by a physical gap and each syllable itself is arranged in a top-to-bottom fashion. Lee and Taft (2009, 2011) have suggested that this visuospatial feature can help prevent confusion when Hangul letters are placed in an incorrect position/slot (i.e., causing a reduced or nonexistent TL effect). In Chinese, the top-bottom structure resembles this special visuospatial feature of Hangul syllables in that the radicals in this structure are also arranged in a top-to-bottom fashion and, as such, the top-bottom structure could have a similar impact in the orthographic processing. Further work is definitely needed to determine if this is the case and, if so, what the underlying mechanism is. It is interesting to note that researchers have known for a long time that adults have more difficult in judging spatial location or orientations of an object when the judgment is with respect to the left-right axis than the up-down axis (e.g., Farrell, 1979). Currently there is little agreement on the explanation for why making position judgments is more difficult with respect to the left-right axis. Several factors have been suggested, including verbal labelling (e.g., Sholl & Egeth, 1981), the perception of symmetry (e.g., Brandt & Mackavey, 1981), and body-centred orientation (e.g., van der Ham et al., 2021).

It might be worth examining in the future whether the left-right and up-down axes difference has some relationship with the different pattern of TL (or TR) effects in Korean Hangul and Chinese characters. Another question that might be interesting to investigate in the future is that whether any TR effects can be found with Japanese Kanji characters which originated from Chinese characters and therefore are similar to Chinese characters in terms of shape, semantics and pronunciation.

3.3 Conclusion

The main goal of this dissertation was to directly investigate whether there is a TR effect in Chinese character recognition when better control of the character structure and the radical shape and size are implemented. The first solid evidence of a TR effect was found in these experiments, providing support for the position-general view of radical representation, the noisy position coding models, and the idea that position flexible orthographic representations and processing are shaped by the language environment. Further investigation and study of how and why the structure impacts TR effects is needed in order to provide additional evidence concerning this issue.

References

Andrews, S. (1996). Lexical retrieval and selection processes: Effects of transposed-letter confusability. *Journal of Memory and Language*, *35*(6), 775–800. https://doi.org/10.1006/jmla.1996.0040

Bates, D., Maechler, M., Bolker, B., Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, *67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Brandt, J., & Mackavey, W. (1981). Left-Right Confusion and the Perception of Bilateral Symmetry. *International Journal of Neuroscience*, *12*(2), 87–94. https://doi.org/10.3109/00207458108985793

Cai, H. D., Qi, X. L., Chen, Q. R., & Zhong, Y. (2012). Effects of phonetic radical position on the regularity effect for naming pictophonetic characters. *Acta Psychologica Sinica*, *44*(7), 868–881. https://doi.org/10.3724/SP.J.1041.2012.00868

Cai, Q., & Brysbaert, M. (2010). SUBTLEX-CH: Chinese word and character frequencies based on film subtitles. *PloS One*, *5*(6), e10729–e10729. https://doi.org/10.1371/journal.pone.0010729

Chang, Y., Welbourne, S., & Lee, C. (2016). Exploring orthographic neighborhood size effects in a computational model of Chinese character naming. *Cognitive Psychology*, *91*, 1–23. https://doi.org/10.1016/j.cogpsych.2016.09.001

Chauncey, K., Holcomb, P., & Grainger, J. (2008). Effects of stimulus font and size on masked repetition priming: An event-related potentials (ERP) investigation. *Language and Cognitive Processes: Cracking the Orthographic Code*, *23*(1), 183–200. https://doi.org/10.1080/01690960701579839

Chen, Y. C., & Yeh, S. L. (2015). Binding radicals in Chinese character recognition: Evidence from repetition blindness. *Journal of Memory and Language*, *78*, 47–63. https://doi.org/10.1016/j.jml.2014.10.002

Chen, Y., & Yeh, S. (2017). Examining radical position and function in Chinese character recognition using the repetition blindness paradigm. *Language, Cognition and Neuroscience*, *32*(1), 37–54. https://doi.org/10.1080/23273798.2016.1227856

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review*, *108*(1), 204–256. https://doi.org/10.1037/0033-295X.108.1.204

Davis, C. J. (2010). The spatial coding model of visual word identification. *Psychological Review*, *117*, 713–758. http://dx.doi.org/10.1037/a0019738

Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of*

Neuroscience Methods, *134*(1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Ding, G., Peng, D., & Taft, M. (2004). The nature of the mental representation of radicals in Chinese: A priming study. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *30*(2), 530–539. https://doi.org/10.1037/0278-7393.30.2.530

Dufau, S., Grainger, J., & Holcomb, P. (2008). An ERP investigation of location invariance in masked repetition priming. *Cognitive, Affective, & Behavioral Neuroscience*, *8*(2), 222–228. https://doi.org/10.3758/CABN.8.2.222

Duñabeitia, J. A., Perea, M., & Carreiras, M. (2007). Do transposed-letter similarity effects occur at a morpheme level? Evidence for morpho-orthographic decomposition. *Cognition*, *105*(3), 691–703. https://doi.org/10.1016/j.cognition.2006.12.001

Farrell, W. S. (1979). Coding left and right. *Journal of Experimental Psychology: Human Perception and Performance*, *5*(1), 42–51. https://doi.org/10.1037/0096-1523.5.1.42

Forster, K., & Davis, C. (1984). Repetition priming and frequency attenuation in lexical access. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *10*(4), 680–698. https://doi.org/10.1037/0278-7393.10.4.680

Frankish, C., & Turner, E. (2007). SIHGT and SUNOD: The role of orthography and phonology in the perception of transposed letter anagrams. *Journal of Memory and Language*, *56*(2), 189–211. https://doi.org/10.1016/j.jml.2006.11.002

Frost, R. (2012). Towards a universal model of reading. *The Behavioral and Brain Sciences*, *35*(5), 263–279. https://doi.org/10.1017/S0140525X11001841

Gomez, P., Ratcliff, R., Perea, M., & Gomez, P. (2008). The overlap model: A model of letter position coding. *Psychological Review*, *115*(3), 577–600. https://doi.org/10.1037/a0012667

Grainger, J., & Jacobs, A. M. (1996). Orthographic processing in visual word recognition: A multiple read-out model. *Psychological Review*, *103*(3), 518–565. https://doi.org/10.1037/0033-295X.103.3.518

Grainger, J., & van Heuven, W. J. B. (2004). Modeling letter position coding in printed word perception. In P. Bonin (Ed.), *Mental lexicon: "Some words to talk about words"* (pp. 1–23). Nova Science Publishers.

Grainger, J., & Ziegler, J. C. (2011). A dual-route approach to orthographic processing. *Frontiers in Psychology*, *2*, 54–54. https://doi.org/10.3389/fpsyg.2011.00054

Grainger, J., Kiyonaga, K., & Holcomb, P. (2006). The time course of orthographic and phonological code activation. *Psychological Science*, *17*(12), 1021–1026. https://doi.org/10.1111/j.1467-9280.2006.01821.x

Gu, J., & Li, X. (2015). The effects of character transposition within and across words in Chinese reading. *Attention, Perception, & Psychophysics*, *77*(1), 272–281. https://dx.doi.org/10.3758/s13414-014-0749-5

Hinton, G. E. (1989). Connectionist learning procedures. *Artificial Intelligence*, *40*, 185–234. https://doi.org/10.1016/0004-3702(89)90049-0

Holcomb, P. J., & Grainger, J. (2006). On the time course of visual word recognition: An event-related potential investigation using masked repetition priming. *Journal of Cognitive Neuroscience*, *18*(10), 1631–1643. https://doi.org/10.1162/jocn.2006.18.10.1631

Hsiao, J. (2011). Visual field differences in visual word recognition can emerge purely from perceptual learning: Evidence from modeling Chinese character pronunciation. *Brain and Language*, *119*(2), 89–98. https://doi.org/10.1016/j.bandl.2011.04.003

Jacobs, R. A. (1988). Increased rates of convergence through learning rate adaptation. *Neural Networks*, *1*(4), 295–307. https://doi.org/10.1016/0893-6080(88)90003-2

Kinoshita, S., & Norris, D. (2010). Masked priming effect reflects evidence accumulated by the prime. *The Quarterly Journal of Experimental Psychology*, *63*(1), 194–204. https://doi.org/10.1080/17470210902957174

Kiyonaga, K., Grainger, J., Midgley, K., & Holcomb, P. (2007). Masked cross-modal repetition priming: An event-related potential investigation. *Language and Cognitive Processes*, *22*(3), 337–376. https://doi.org/10.1080/01690960600652471

Ktori, M., Kingma, B., Hannagan, T., Holcomb, P., & Grainger, J. (2014). On the time-course of adjacent and non-adjacent transposed-letter priming. Journal of *Cognitive Psychology*, *26*(5), 491–505. https://doi.org/10.1080/20445911.2014.922092

Lally, C., Taylor, J. S. H., Lee, C. H., & Rastle, K. (2020). Shaping the precision of letter position coding by varying properties of a writing system. *Language, Cognition and Neuroscience*, *35*(3), 374–382. https://doi.org/10.1080/23273798.2019.1663222

Lee, C. H., & Taft, M. (2009). Are onsets and codas important in processing letter position? A comparison of TL effects in English and Korean. *Journal of Memory and Language*, *60*(4), 530–542. https://doi.org/10.1016/j.jml.2009.01.002

Lee, C. H., & Taft, M. (2011). Subsyllabic structure reflected in letter confusability effects in Korean word recognition. *Psychonomic Bulletin & Review*, *18*(1), 129–134. https://doi.org/10.3758/s13423-010-0028-y

Lee, C.-Y. (2008). Rethinking of the regularity and consistency effects in reading. *Language and Linguistics*, *9*(1), 177–186.

Lerner, I., Armstrong, B., & Frost, R. (2014). What can we learn from learning models about sensitivity to letter-order in visual word recognition? *Journal of Memory and Language*, *77*, 40–58. https://doi.org/10.1016/j.jml.2014.09.002

Lin, S., Chen, H., Zhao, J., Li, S., He, S., & Weng, X. (2011). Left-lateralized N170 response to unpronounceable pseudo but not false Chinese characters—the key role of orthography. *Neuroscience*, *190*, 200–206. https://doi.org/10.1016/j.neuroscience.2011.05.071

Lopez-Calderon, J., & Luck, S. J. (2014). ERPLAB: An open-source toolbox for the analysis of event-related potentials. *Frontiers in human neuroscience*, *8*, 213. https://doi.org/10.3389/fnhum.2014.00213

Lupker, S. J., & Davis, C. J. (2009). Sandwich priming: A method for overcoming the limitations of masked priming by reducing lexical competitor effects. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*(3), 618–639. https://doi.org/10.1037/a0015278

Lupker, S. J., Nakayama, M., & Perea, M. (2015). Is there phonologically based priming in the same-different task? Evidence from Japanese-English bilinguals. *Journal of Experimental Psychology: Human Perception and Performance*, *41*(5), 1281–1299. https://doi.org/10.1037/xhp0000087

Lupker, S. J., Nakayama, M., & Yoshihara, M. (2018). Phonologically based priming in the same-different task with L1 readers. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *44*(8), 1317–1324. https://doi.org/10.1037/xlm0000515

Lupker, S. J., Perea, M., & Nakayama, M. (2015). Non-cognate translation priming effects in the same–different task: Evidence for the impact of "higher level" information. *Language, Cognition and Neuroscience*, *30*(7), 781–795. https://doi.org/10.1080/23273798.2015.1015430

MATLAB 2020a, The MathWorks, Inc., Natick, Massachusetts, United States.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: I. An account of basic findings. *Psychological Review*, *88*(5), 375–407. https://doi.org/10.1037/0033-295X.88.5.375

Ministry of Education of the People's Republic of China. (2013, June 5). *国务院关于公布《通用规范汉字表》的通知* [Notice of the State Council on the Publication of the Table of General Standard Chinese Characters]. The State Council of the People's Republic of China. http://www.gov.cn/zwgk/2013-08/19/content_2469793.htm

Misra, M., & Holcomb, P. (2003). Event–related potential indices of masked repetition priming. *Psychophysiology*, *40*(1), 115–130. https://doi.org/10.1111/1469-8986.00012

Norris, D. (2006). The Bayesian reader: Explaining word recognition as an optimal Bayesian decision process. *Psychological Review*, *113*(2), 327–357. https://doi.org/10.1037/0033-295X.113.2.327

Norris, D. (2009). Putting it all together: A unified account of word recognition and reaction-time distributions. *Psychological Review*, *116*(1), 207–219. https://doi.org/10.1037/a0014259

Norris, D., Kinoshita, S., & van Casteren, M. (2010). A stimulus sampling theory of letter identity and order. *Journal of Memory and Language*, *62*(3), 254–271. https://doi.org/10.1016/j.jml.2009.11.002

Norris, D., Kinoshita, S., Hall, J., & Henson, R. (2018). Is reading automatic? Are the ERP correlates of masked priming really lexical? *Language, Cognition and Neuroscience*, *33*(9), 1152–1167. https://doi.org/10.1080/23273798.2018.1493516

Perea, M., & Carreiras, M. (2006). Do transposed-letter similarity effects occur at a prelexical phonological level? *The Quarterly Journal of Experimental Psychology*, *59*(9), 1600–1613. https://doi.org/10.1080/17470210500298880

Perea, M., & Lupker, S. J. (2003). Transposed-letter confusability effects in masked form priming. In S. Kinoshita & S.J. Lupker (Eds.), *Masked priming: State of the art* (pp. 97–120). Hove, UK: Psychology Press.

Perea, M., & Lupker, S. J. (2004). Can CANISO activate CASINO? Transposed-letter similarity effects with nonadjacent letter positions. *Journal of Memory and Language*, *51*(2), 231–246. https://doi.org/10.1016/j.jml.2004.05.005

Perea, M., & Pérez, E. (2009). Beyond alphabetic orthographies: The role of form and phonology in transposition effects in Katakana. *Language and Cognitive Processes*, *24*(1), 67–88. https://doi.org/10.1080/01690960802053924

Perea, M., Abu Mallouh, R., & Carreiras, M. (2010). The search for an input-coding scheme: Transposed-letter priming in Arabic. *Psychonomic Bulletin & Review*, *17*(3), 375–380. https://doi.org/10.3758/PBR.17.3.375

Perea, M., Moret-Tatay, C., & Carreiras, M. (2011). Facilitation versus inhibition in the masked priming same–different matching task. *The Quarterly Journal of Experimental Psychology*, *64*(10), 2065–2079. https://doi.org/10.1080/17470218.2011.582131

Perea, M., Winskel, H., & Gomez, P. (2018). How orthographic-specific characteristics shape letter position coding: The case of Thai script. *Psychonomic Bulletin & Review*, *25*(1), 416–422. https://doi.org/10.3758/s13423-017-1279-7

Perfetti, C. A., & Tan, L. H. (1998). The time course of graphic, phonological, and semantic activation in Chinese character identification. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *24*(1), 101–118. https://doi.org/10.1037/0278-7393.24.1.101

Perfetti, C. A., Liu, Y., & Tan, L. H. (2005). The lexical constituency model: Some implications of research on chinese for general theories of reading. *Psychological Review*, *112*(1), 43–59. https://doi.org/10.1037/0033-295X.112.1.43

Plaut, D. C. (1997). Structure and Function in the Lexical System: Insights from Distributed Models of Word Reading and Lexical Decision. *Language and Cognitive Processes*, *12*(5-6), 765–806. https://doi.org/10.1080/016909697386682

Plaut, D. C., McClelland, J. L., Seidenberg, M. S., & Patterson, K. (1996). Understanding normal and impaired word reading: computational principles in quasi-regular domains. *Psychological Review*, *103*(1), 56–115. https://doi.org/10.1037/0033-295X.103.1.56

R Core Team (2021). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/

Rastle, K., Lally, C., & Lee, C. H. (2019). No flexibility in letter position coding in korean. *Journal of Experimental Psychology: Human Perception and Performance*, *45*(4), 458–473. https://doi.org/10.1037/xhp0000617

Rimzhim, A., Johri, A., Kelty-Stephen, D. G., & Fowler, C. A. (2021). Transposition effects in an Aksharic writing system: The case of hindi. *Language and Speech*, *64*(4), 804–838. https://doi.org/10.1177/0023830920971315

RStudio Team (2021). RStudio: Integrated Development for R. RStudio, Inc., Boston, MA. URL http://www.rstudio.com/

Rumelhart, D. E., & McClelland, J. L. (1982). An interactive activation model of context effects in letter perception: II. The contextual enhancement effect and some tests and extensions of the model. *Psychological Review*, *89*(1), 60–94. https://doi.org/10.1037/0033-295X.89.1.60

Rumelhart, D. E., Hinton, G. E., & Williams, R. J. (1986). Learning internal representations by error propagation. In D. E. Rumelhart & J. L. McClelland (Eds.). *Parallel distributed processing: Explorations in the microstructure of cognition (Vol. 1)*. Cambridge, MA: MIT Press.

Russell Lenth (2021). emmeans: Estimated Marginal Means, aka Least-Squares Means. R package version 1.4. URL https://CRAN.R-project.org/package=emmeans

Schoonbaert, S., & Grainger, J. (2004). Letter position coding in printed word perception: Effects of repeated and transposed letters. *Language and Cognitive Processes*, *19*(3), 333–367. https://doi.org/10.1080/01690960344000198

Shillcock, R., Ellison, T. M., & Monaghan, P. (2000). Eye-fixation behavior, lexical storage, and visual word recognition in a split processing model. *Psychological Review*, *107*(4), 824–851. https://doi.org/10.1037/0033-295X.107.4.824

Sholl, M. J., & Egeth, H. E. (1981). Right-left confusion in the adult: A verbal labeling effect. *Memory & Cognition*, *9*(4), 339-350. https://doi.org/10.3758/BF03197558

Su, I. F., Mak, S. C. C., Cheung, L. Y. M., & Law, S. P. (2012). Taking a radical position: Evidence for position-specific radical representations in Chinese character recognition using masked priming ERP. *Frontiers in Psychology*, *3,* 333. https://doi.org/10.3389/fpsyg.2012.00333

Taft, M. (2006). Processing of characters by native Chinese readers. In P. Li, L. Tan, E. Bates, & O. Tzeng (Eds.), *The Handbook of East Asian Psycholinguistics* (pp. 237–249). Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9780511550751.023

Taft, M., & Zhu, X. (1997). Submorphemic processing in reading Chinese. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *23*(3), 761–775. https://doi.org/10.1037/0278-7393.23.3.761

Taft, M., Zhu, X., & Peng, D. (1999). Positional specificity of radicals in chinese character recognition. *Journal of Memory and Language*, *40*(4), 498–519. https://doi.org/10.1006/jmla.1998.2625

Tao, H., & Xiao R. (2012) *The UCLA Chinese Corpus* (2nd edition). UCREL, Lancaster.

The Unicode Consortium. (2020). East Asia. *The Unicode Standard Version 13.0 – Core Specification* (pp. 709–762). Unicode Consortium. https://www.unicode.org/versions/Unicode13.0.0/ch18.pdf

Tsang, Y. K., & Chen, H.-C. (2009). Do position-general radicals have a role to play in processing Chinese characters*? Language and Cognitive Processes*, *24*(7-8), 947–966. https://doi.org/10.1080/01690960802154615

van der Ham, I. J., Dijkerman, H. C., & van Stralen, H. E. (2021). Distinguishing left from right: A large-scale investigation of left–right confusion in healthy individuals. *Quarterly Journal of Experimental Psychology*, *74*(3), 497–509. https://doi.org/10.1177/1747021820968519

Velan, H., & Frost, R. (2009). Transposition effects are not universal: The impact of transposing letters in Hebrew. *Journal of Memory and Language*, *61*(3), 285–302. https://doi.org/10.1016/j.jml.2009.05.003

Velan, H., & Frost, R. (2011). Words with and without internal structure: What determines the nature of orthographic and morphological processing? *Cognition*, *118*(2), 141–156. https://doi.org/10.1016/j.cognition.2010.11.013

Wang, J., Cheng, L., Maurer, U., & Chen, H.-C. (2022). Role of radical position and character configuration in Chinese handwritten production. *Reading and Writing* (2022). https://doi.org/10.1007/s11145-022-10348-5

Whitney, C. (2001). How the brain encodes the order of letters in a printed word: The SERIOL model and selective literature review. *Psychonomic Bulletin & Review*, *8*(2), 221–243. https://doi.org/10.3758/BF03196158

Winskel, H., Perea, M., & Ratitamkul, T. (2012). On the flexibility of letter position coding during lexical processing: Evidence from eye movements when reading

Thai. *Quarterly Journal of Experimental Psychology*, *65*(8), 1522–1536. https://doi.org/10.1080/17470218.2012.658409

Witzel, N., Qiao, X., & Forster, K. (2011). Transposed letter priming with horizontal and vertical text in Japanese and English readers. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(3), 914–920. https://doi.org/10.1037/a0022194

Xing, H. (2007). The analysis and computational study of the statistical features of modern Chinese characters. Beijing: The Commercial Press

Xing, H., Shu, H., & Li, P. (2004). The acquisition of Chinese characters: Corpus analyses and connectionist simulations. *Journal of Cognitive Science, 5*(1), 1–49.

Yang, H., Chen, J., Spinelli, G., Lupker, S., & Yang, H. (2019). The impact of text orientation on form priming effects in four-character Chinese words. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *45*(8), 1511–1526. https://doi.org/10.1037/xlm0000655

Yang, H., Hino, Y., Chen, J., Yoshihara, M., Nakayama, M., Xue, J., & Lupker, S. J. (2020). The origins of backward priming effects in logographic scripts for four-character words. *Journal of Memory and Language*, *113*, 104107–. https://doi.org/10.1016/j.jml.2020.104107

Yang, J., McCandliss, B., Shu, H., & Zevin, J. (2009). Simulating language-specific and language-general effects in a statistical learning model of Chinese reading. *Journal of Memory and Language*, *61*(2), 238–257. https://doi.org/10.1016/j.jml.2009.05.001

Yang, J., Shu, H., McCandliss, B., & Zevin, J. (2013). Orthographic influences on division of labor in learning to read Chinese and English: Insights from computational modeling. *Bilingualism: Language and Cognition*, *16*(2), 354–366. https://doi.org/10.1017/S1366728912000296

Yeh, S.-L., & Li, J.-L. (2002). Role of structure and component in judgments of visual similarity of Chinese characters. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(4), 933–947. https://doi.org/10.1037/0096-1523.28.4.933

Yum, Y. N., Su, I. F., & Law, S. P. (2015). Early effects of radical position legality in Chinese: An ERP study. *Scientific Studies of Reading*, *19*(6), 456–467. https://doi.org/10.1080/10888438.2015.1081204

Zhou, X., & Marslen-Wilson, W. (1999). The nature of sublexical processing in reading Chinese characters. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *25*(4), 819–837. https://doi.org/10.1037/0278-7393.25.4.819

Appendices

Appendix A: NCR and CR characters used as targets in Experiment 2.

NCR characters		CR characters	
蝎	哱	黠	魛
槿	须	黏	盼
羯	险	横	咳
瑾	勃	鞋	虹
竭	胫	龊	叙
揭	鸩	鲜	勋
勤	鹝	精	弭
喝	郑	蝉	玩
隔	限	睹	帖
彭	枕	靖	鸣
赔	叔	睛	帕
酣	耶	鲇	呷
喁	艰	龃	勍
琣	弪	确	鸡
鹃	阴	联	助
焙	阳	斌	劫
睑	形	勒	坝
眼	邵	梯	轩
脸	劲	鸽	町
检	邪	婵	肛
培	杉	皑	如
啄	彤	粕	此
彬	妩	舶	动
脖	阵	核	灯
豚	邢	鸭	戏
酖	叫	烛	妃
配	旧	朕	叶
耕	队	蚌	奴
娟	邓	鸵	驭
耽	引	贿	劝

Appendix B: Characters used as the reference and target stimuli for the "different" trials in Experiment 3.

Reference	Target	Reference	Target
碟	襦	曝	蹭
疑	蟠	皤	璀
彰	濡	糖	歌
酿	孺	稿	僧
缪	镌	嘻	榧
数	膀	鲤	榛
谨	椹	骸	搞
缜	睢	骼	楝
稚	插	飒	楦
缘	揣	路	粳
铸	椋	跨	楂
践	鹂	跺	睫
敢	锒	楠	短
假	唱	瑰	搁
彩	惧	跬	揭
旋	绯	硬	椒
凑	绮	程	惰
敛	渚	棍	锋
祸	婧	琛	棰
敏	绱	琚	犄
绫	隗	釉	嗟
绵	皲	椤	教
酚	借	矬	啥
帷	特	甥	峰
赦	剧	啦	埋
酝	涓	睁	姬
淮	俱	粒	诚
谁	浣	斜	浠
海	烘	职	眠
酒	胱	舵	绡
效	脐	皎	娴
凄	娲	竫	涝
朗	浜	样	娌
耙	娉	哦	剞
浩	绾	校	胡
郫	狸	鸪	保

耘	砾	鸬	烂
绦	钩	竘	娜
既	垮	相	撮
祖	绛	城	珏
缸	俊	炸	诲
残	挎	映	姝
绑	姣	咽	股
珍	话	鸥	刻
籽	转	柿	刮
视	板	姹	肥
佳	版	珑	贩
询	规	眬	听
钐	拌	码	利
改	妲	坡	驴
证	驷	肺	扮
诊	枥	坯	佗
级	住	呀	妤
收	妞	坛	伤
休	姒	吟	则
妆	杈	呗	乩
伐	纭	机	归
舛	吃	帆	仕
礼	冲	叭	仆
冯	杞	叮	什

Appendix C: NCR and CR characters used as the reference and target stimuli for the “same” trials in Experiment 4.

NCR characters		CR characters	
丞	苫	耸	垦
莆	卉	垄	泵
宕	苣	岂	恳
茎	苑	暑	翁
宛	馨	贡	呈
巢	芯	晋	岩
煎	骂	忌	壁
宠	宜	裂	晨
芬	宇	皇	李
寓	雪	墨	奋
异	杂	袋	季
莱	客	念	架
罪	节	类	奇
完	家	星	思
豢	芷	聂	冒
茁	骛	岳	汞
冗	笃	秃	奢
茧	芋	柴	昆
宋	茉	轰	贷
苗	芒	崩	泉
筑	煮	昏	柔
芭	宙	督	贺
熊	荡	辈	怒
哭	牢	香	袭
苦	寻	志	货
杰	笑	显	资
字	英	圣	忘
点	它	最	员

Appendix D: Characters used as the reference and target stimuli for the “different” trials in Experiment 4.

Reference	Target	Reference	Target
鉴	塑	毙	烫
俞	妾	髻	龛
葱	贸	苇	弩
盔	宪	啬	奕
荐	妄	睾	藉
乏	亏	茫	冥
姿	患	悬	窝
鼻	蜜	召	忽
余	允	震	策
景	素	笨	夏
暴	婆	骨	堂
萨	套	楚	落
梦	容	黑	基
息	金	安	名
娄	雯	翟	尧
芳	栗	肴	寥
蔽	熙	亢	炙
贤	岗	苛	吾
嘉	晃	贯	巷
奉	芝	盐	莲
怨	符	惩	奈
堡	著	朵	荒
惹	染	典	卷
笔	替	秀	莫
型	麦	华	共
监	丽	台	务
声	条	号	早
等	爱	只	怎
忿	穹	龚	骛
渠	葵	荤	孚
皂	姜	霆	蓉
脊	盆	孬	茬
贫	哲	凳	禽
咒	昂	筋	紫
慈	奏	弯	爹
夺	宁	售	窃

育	青	范	冠
虽	登	荣	兵
态	究	突	导
具	蒂	票	量
买	弟	花	写
其	希	然	些
券	苍	苋	柒
孪	萧	盂	翌
帘	茱	怂	芹
弊	蒸	吝	旱
契	肾	旨	斧
兜	苹	笛	募
蕾	辜	茄	壳
尖	桑	盟	琴
赞	累	烈	愚
毕	苏	草	勇
签	奖	箱	露
画	背	药	费
岁	幸	弄	兄
变	总	实	告

Curriculum Vitae

Name Zian Chi

Post-secondary Education and Degree

Nankai University
Tianjin, China
2007-2011 Bachelor of Science

Nankai University
Tianjin, China
2007-2011 Bachelor of Economics

Nanjing Normal University
Nanjing, Jiangsu, China
2011-2014 Master of Education

The University of Western Ontario
London, Ontario, Canada
2017-2022 (expected) Doctor of Philosophy

Related Work Experience

MEd Research
Nanjing Normal University, Dr. Houde Cai
2011-2014 Hemispheric Differences in Recognition of Chinese PS and SP Characters

Research Team Member
Nanjing Normal University, Dr. Hong Fu
2012-2013 Survey of the Happiness of the Elderly in Jiangsu Province (by Nanjing Normal University and Jiangsu Charity Federation)

Graduate Teaching Assistant

The University of Western Ontario

2017-2019 Introductory Psychology

2019-2020 Research Methods in Psychology

2019-2021 Statistics for Psychology

PhD Research

The University of Western Ontario, Dr. Stephen Lupker

2017-2022 Examines the transposed radical effect in Chinese character recognition

Research Assistant

The University of Western Ontario, Dr. Stephen Lupker

2021-2022

Conference Presentation

Chi, Z. & Lupker. S. J. (November 2021) Modeling the Transposed Radical Effect in Chinese Character Recognition. Poster presented at the 62nd Annual Meeting of the Psychonomic Society, Online.

Chi, Z. & Lupker. S. J. (November 2020) The Effect of Phonology and Lexical Status in the Masked Priming Same-Different Matching Task. Poster presented at the 61st Annual Meeting of the Psychonomic Society, Online.

Chi, Z., Pan, X., & Lupker. S. J. (June 2019) The Flexibility of Radical Position Coding in Chinese Character Recognition: Evidence from Transposed Radical Priming Effects. Poster presented at the the 29th Annual meeting of the Canadian Society for Brain, Behaviour and Cognitive Science, Waterloo, Ontario, Canada

Chi, Z., Pan, X., & Lupker, S. J. (November 2018) A Further Examination of Transposed Radical Priming Effects in Chinese Character Recognition. Poster presented at the 59th Annual Meeting of the Psychonomic Society, New Orleans, Louisiana, USA

Honours and Awards

Second Prize of Excellent Undergraduate Scholarship

Nankai University

2007-2008, 2008-2009

Western Graduate Research Scholarship

The University of Western Ontario
2017-2021