Behavioral and Neuronal Headstart Effects in Visual Chinese Phonogram Recognition

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Abstract

Chinese phonograms are composed by a semantic radical and a phonetic radical, which provide naturalistic language materials to study the different levels of the processes involved in visual character recognition. We used a headstart paradigm to examine the preparation readers could gain from pre-exposing a part of a written target stimulus. When native Taiwan Mandarin Chinese readers saw the radical 100 ms before the whole character, they responded faster in a lexical decision task. In addition, we found an interaction effect between character structures and types of headstart which indicated that the headstart effect was not only due to visual repetition. We further investigated the neuronal substrates of processing visual Chinese character using magnetoencephalography (MEG) which provides a good temporal resolution for investigating the neuronal processes. MEG also has a better spatial resolution than electroencephalography which allows us to have a better estimation on the brain regions involved in the processes. Our results indicated that the headstart effect was reflected in induced gamma band activity at around 70~100 Hz over posterior occipital areas. When the readers saw the headstart, the induced gamma synchronization was weaker in comparison to when they did not see the headstart. We replicated the interaction effect between character structures and types of headstart behaviorally, but the induced gamma power did not reflect it. Given that seeing a headstart is a special situation which allows the beginning of processing the target 100 ms ahead, we speculate that the induced gamma responses are not only due to the visual repetition, but also due to dynamics within the linguistic-perceptual network. Further study is needed for clarifying the functional role of induced gamma oscillatory activity at the posterior area.

Keywords: Chinese phonogram, radical, headstart effect, magnetoencephalography, gamma oscillation

1. Introduction

In the past few decades, psycholinguistic studies provide a growing understanding on how human readers process visually presented words (for a comprehensive overview see Balota, 1994; Balota, et al., 2006) and have proposed computational models suggesting the hierarchy and interaction between different levels of representation (McClelland & Rumelhart, 1981; Coltheart, et al., 2001). In addition, electrophysiology data recording provides insights on the time course (Graigner & Holocomb, 2009) during reading tasks and for difference psycholinguistic levels (Bentin, et al., 1999). Several ERP components were identified for corresponding functional roles during visual word recognition. For instance, at around 150 ms from the onset of a visual word stimulus, the retinotopic mapping of visual forms onto location-specific letters was detected (N/P 150). N170 components indicated an earlier perceptual detection of orthographical forms. Liu and colleagues (2003) suggested that P200 is related to the orthographic and phonological processing of radicals in Chinese phonogram recognition processes. The amplitude of N250 components was sensitive to the difference between pseudophomophone and its target (brane-BRAIN). P325 was showed to be associated with lexical identification; at this time point, the whole word was identified. Phonological processing was detected at around 350 ms after the onset of stimulus (N350). In addition, N400 components are related to the semantic processing of the lexicons (Kutas & Federmeier, 2000). Most of the studies performed in this domain were based on alphabetic languages. Alphabetic languages have a grapheme to phoneme mapping. For instance, Finnish orthography is considered to be transparent (a.k.a. shallow) because it has nearly one to one grapheme to phoneme mapping, Whereas English grapheme is less regular to its corresponding phoneme therefore is said to be opaque (a.k.a. deep) (Frost et al., 1987). The orthographic depth of Chinese characters is often considered to be deep: unlike reading an alphabetic grapheme, one can hardly read the phoneme by looking at the Chinese ideographs. Nevertheless, one type of Chinese characters, the “phonogram”, is composed by a semantic unit and a phonetic unit which provide the corresponding information. These units are called “radicals”: the semantic radical cues the meaning while the phonetic radical cues the pronunciation of the character. Given that phonograms are more than 80% in modern Chinese (Hsiao & Shillcock, 2006; Lee, 2008), Chinese written system is not entirely opaque. In fact, phonograms provide natural language materials for disentangling the representations and processing of semantic and phonological information during visual word recognition. The current study uses these properties of phonograms to investigate the processes of visual character recognition.

There is a growing attention on the Chinese language processing (Zhou & Shu, in press) and many of them are aware of the insights one can gain from studying Chinese phonograms (Kuo et al., 2003; Perfetti et al., 2005). However, none of the previous studies tested the direct relation between the radical and its belonging character. The current study uses a headstart paradigm which enabled us to directly use the radical to examine the processing of its belonged character. The headstart paradigm used in this study is a psychophysiological technique (Eriksen & Eriksen, 1974) to pre-expose a part of visual target stimuli in order to prepare for the task performance. Previous studies demonstrated that this paradigm was sensitive enough to study the visual processing of morphological units (Jarvella et al., 1987; Schreuder et al., 1990) in alphabetic orthography. Pre-exposition of the semantic or phonetic unit of a character might differ in their effect on the processes of character recognition and were studied by measuring the reaction time in the current study. Although the semantic radical and phonetic radical are by definition providing different types of information, it has been an issue whether the radical is processed as a sublexical unit during Chinese character recognition or not. Feldman and Siok (1997, 1999) showed that semantic radicals contributed to the process of Chinese character recognition. Ding, Peng and Taft (2004) found the positional specificity of the radicals plays a role. Hsiao and colleagues (Hsiao & Shillcock, 2005; Hsiao et al., 2007b) further demonstrated that the semantic and phonetic radicals were first projected onto different hemispheres. Following the previous studies, we used the headstart to further examine whether the radicals were used for native readers to identify the whole character. We hypothesized that if the radical was processed as a functional unit for recognizing the character, the readers would react faster in a lexical decision task.

To our knowledge, the current study is the first study which examines the headstart effect in Chinese phonograms on both behavioral and neuronal levels. Hsiao et al. (2007a) used a cueing paradigm which shared some similarity with our headstart paradigm. They drew the readers’ attention to the left or to the right of the screen prior the presentation of a SP character (i.e. a phonogram which has a semantic radical on the left and a phonetic radical on the right) in the middle of the screen. In contrast, we presented the radical at a position where it was legally situated in the natural language which avoided the cue being distractive. Hsiao and colleagues (2007b) also studied SP characters and its mirroring structure PS as in the current study, but we used these character structures for different reasons. They used these two structures because of the spatial arrangement allowed them to study the spilt fovea theory. Current study selected these two structures because 72% percent of phonograms have a left-right structure. Among this distribution, 90% has the semantic radical on the left and the phonetic radical on the right (Hsiao & Shillcock, 2006). There is a small percentage for other arrangements of radicals, such as top-down, outer-inner and others that were not covered in this study. In current study, we used a standard lexicon decision task which did not enforce either the semantic reading or the processing of phonological information. Our study could therefore examine the processing of visual Chinese character recognition naturalistically.

Apart from the behavioural headstart effect, this study also explored the neuronal substrates of the processes of Chinese visual character. Human electrophysiology data showed that the neuronal synchrony plays a role in integrating different types of information during language processing (Bastiaansen & Hagoort, 2006). In addition, induced gamma band activity (30~100Hz) is important for semantic processing (Hald et al., 2006) and it is associated in the binding of words during reading (Dalal et al., 2009). Studies have suggested that induced gamma activity is not restricted to particular cognitive processes (Jensen et al., 2007; Schneider et al., 2011), but rather binds a fundamental process in cortical computation which enables many cognitive processes (Fries, 2009). Wu et al. (2009) reported that the neuronal synchrony activity in perceptual areas was modulated by the difficulty in a linguistic task. We hypothesized that the headstart effect will be reflected in the synchronization in the gamma band. In particular we would expect the engagement of visual area not only for early perceptual response to the stimuli, but also for reflecting the processing effort within the linguistic-perceptual network.

This study has one behavioural experiment and one MEG experiment. The goal of the first experiment was to establish the headstart effect in Chinese visual character recognition task in a lexical decision task. The second experiment further explored the headstart effect being reflected by the neuronal synchronization at the gamma band.

2. Method

Except for the trial numbers, measurements (behavioural or neuroimaging methods), the materials and procedures were similar for Experiment 1 and 2. Therefore, the method for these experiments are presented together.

2.1. Participants

Experiment 1

Twenty native speakers of Taiwan Mandarin took part in this study. Among them, fifteen were residing in the Netherlands for at least five months. They all learned Zhu-yin in school (Zhu-yin are non-alphabetic phonetic symbols learned in primary school for annotating the phonemes in Taiwan). Meanwhile, traditional Chinese character is the first written language they used for reading experiences. All of them were rewarded with gift voucher 5 euro for their participation according to DCC procedure.

Experiment 2

Fourteen healthy participants, (mean age 28 ± 3.6 years old; 7 male and 7 female) participated in the experiment. None of them were tested in Experiment 1. All participants had normal or corrected-to-normal vision and were self-reported to be right-handed. They gave written informed consent before the experiment according to general CMO approvals at DCCN. All participants were native speakers of Taiwan Mandarin residing in the Netherlands. Their language experience was identical to the one in Experiment 1. All of them were rewarded with gift voucher 15 euro for their participation according to DCC procedure.

2.2. Materials

The materials consisted of 64 existing Chinese characters and 64 pseudocharacters. These 128 characters were rated above a three point rating on a seven point of familiarity scale (Bai & Schreuder, 2011). All the characters are nouns or are more frequently interpreted as a noun when presented in isolation. Furthermore, the characters which were selected for this study are visually simple. They were mostly composed by only two units and there was no visual overlap between radicals. Characters which cannot stand alone as a meaningful noun were not selected either. In addition, in order to minimize repetition effect, we decided that each radical could only appear at most twice in each experimental section.

Existing characters

The 64 existing characters in the material list characters were divided into two groups according to the positional information of their radicals. Half (32) of the existing characters had a SP character structure while the other 32 characters had a PS structure.

Pseudocharacters

All pseudocharacters were made up by combining an existing semantic radical and one phonetic radical. The same characters from the existing list were used to make up the pseudocharacters for the following reason. This method enabled us, to use the identical semantic radicals and phonetic radicals in existing and pseudocharacters. Thus, we could control the repetition of semantic radicals and phonetic radicals. In addition, the amount of SP and PS pseudocharacters was identical to the SP and PS structure for existing characters. The visual complexity of radicals in the pseudocharacters was controlled since they belonged to the existing character list.

2.3. Design

Experiment 1

There were 128 characters: 64 existing characters and 64 pseudocharacters in the material list (Figure 1). Each participant saw one given character two times: once as a complete character, and another time with either a headstart of its own semantic or phonetic radical. We therefore created two master lists such that the chances of seeing a semantic or a phonetic radical of a certain character were balanced between participants. If one character was presented with a headstart of its phonetic radical in the first list, this character would be presented with a headstart of its semantic radical in the second list. Half of the characters in each master list were presented with a phonetic radical and another half were presented with a semantic radical as headstart. Half of the participants saw the first list and another half saw the second list.

We controlled for the occurrence of certain character with either semantic headstart (S) or phonetic headstart (P) and no-headstart in the two master lists. That is, the order of presenting S/P as headstart or no-headstart was identical for the two master lists. The way to proceed was to list two master lists next to each other. This operation ensured that the occurrence of headstart conditions were mirroring in two lists. Finally, we randomized the combined master lists two times which resulted into two randomized lists. The randomization was done by using a MIX programme (Van Casteren & Davis, 2006).

We measured 1) the distance of occurrence between no-headstart trial (condition1) and headstart trial (condition2) for each given character; 2) the order of occurrence between these two conditions. We concluded that the randomization resulted in an sufficiently balanced situation. In most of the cases, the distance between two experimental conditions was more than 10 trials and the order of occurrence was close to equivalent. Two times randomization on two master lists resulted in four different lists. We further reversed the order of each list such that effects from the order of presentation, e.g. fatigue, could be minimized.

Table 1

The result of two times randomization (Rand 1 and Rand 2)

The distance between Condition 1 and 2			The order of Condition 1 and 2		
	Rand1	Rand2		Rand1	Rand2
>10 trials	119	121	Cond1 before Cond2	62	68
≤10 trials	9	7	Cond2 before Cond1	66	60
Total	128	128		128	128

Number of set of characters. Condition 1: No-headstart (#); Condition 2: headstart (S or P)

Experiment 2

In Experiment 1, 256 trials were presented in total. We repeated the experiment four times for Experiment 2 which thenresulted in four experimental sections with a total of 1024 trials. Each experimental section had 256 trials which was divided equally into two blocks each lasting for about 8 minutes. Participants were given a pause by the end of each block. The order of stimuli presentation was randomized and counterbalance across participants.

The analysis of MEG recordings was performed using the FieldTrip toolbox developed at the Donders Institute for Brain, Cognition and Behaviour (http://www.ru.nl/neuroimaging/fieldtrip) using Matlab R2010b (MathWorks, Natick, MA). The trials were categorized by its character types (real or pseudocharacter), character structures (SP or PS character) and headstart category (#/S/P). The MEG data were first down sampled from 1200 Hz to 600 Hz. We extracted the data from 400 ms before and 600 ms after the target stimuli.

Artifacts were rejected by visually inspecting the variances in channel and trial summary using the visual artifact function in the FieldTrip toolbox. The outliner trials (of recording data, not the experimental trials) or sensors were rejected manually for each trial. Different amount of trials and channels were rejected for each participant. In general, there were at least 84 trials left for no-headstart condition (#) and for headstart conditions (S/P) respectively remained for further analysis. We used a synthetic 3rd order gradient to cancel out the noise. An estimation of the planar gradient for the sensor-level analysis was applied (REF).

Time-frequency representations of power (TFRs; 30~100 Hz) was calculated for each trials using a fast Fourier transform multitaper approach based on a fixed time window of 200 ms and a frequency smoothing of 10 Hz which results in three Slepian tapers. A relative baseline correction was applied from 400 ms to 200 ms prior to the target stimuli. Data sets from one participant were discarded because of severe artifacts at the left temporal and posterior sensors.

2.4. Procedure

Experiment 1

Each participant were placed in front of a computer screen at a distance of approximately 50 cm. The size of each character was 2 cm height and 2 cm width, in KaiU font. The stimuli were in black color (R0, G0, B0) against the white display. Each trial started with a fixation cross displayed for 300 ms. After a 200 ms blank screen followed a headstart presented for 100 ms. The target characters followed immediately after the headstart. As illustrated in Figure 1, the S/P headstart coniditions, the headstart did not appear in the centre of the display; instead, it appears at the legal position in the natural language.

The participants were asked to respond whether the stimuli characters exist in written language or not, as quickly and accurately as possible. They were asked to use their right index finger for a “yes” response, and left index finger for a “no” response. The target stimuli were on the display until the participants responded unless the response time exceeded 1800 ms. After 1800 ms of inter-trial interval, the next trial started.

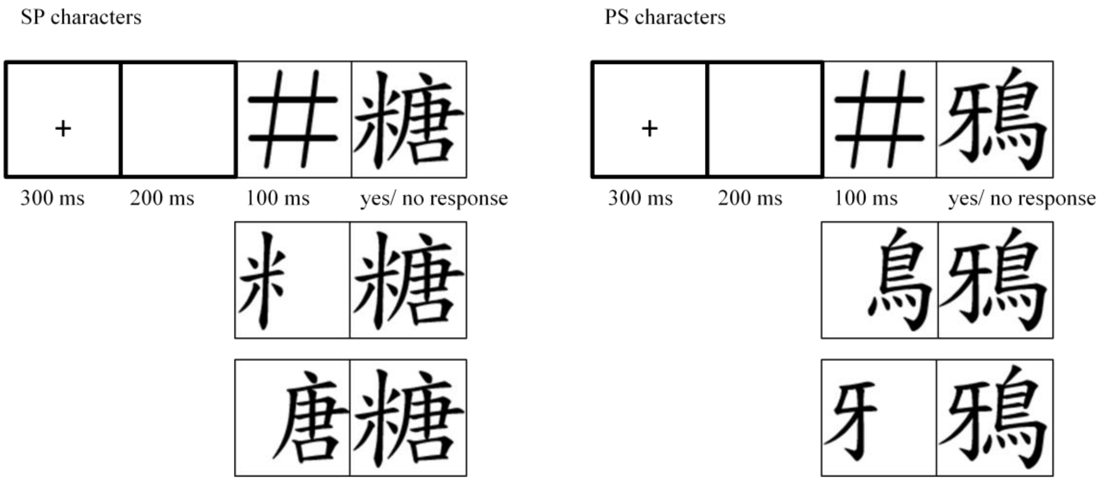

Figure 1. The schematic figure of the headstart paradigm. All six possiblities of presentating headstarts (#/S/P) and character structures (SP/PS). The fixation cross was presented in the centre of the screen for 300ms follwoed by a 200 ms blank screen.Then followed a 100ms no-headstart/headstart presentation and then the target character was presented. The target stay on until the subjet responsed or the duration exceeded for 1800 ms. The intertrial interval is 1800 ms.

Experimental 2

The experimental paradigm was similar to Experiment 1 (see Figure 1). The degree of visual angle was arctan (3.5/ 78). The color of stimuli and display was reversed in Experiment 2. The stimuli were presented in grey (R200, G200, B200) and the display was in black. The illumination of white color (R255, G255, B255) presentation was too high in a dimmed-light MSR (magnetic shielded room) which was too demanding for the participants to fixate on the display. Thus, we decided not to use white color for the stimuli or for the background display. We believed that if the effect would have been strong enough, the experimenters could still find the effect despite of this minor change. For the response participants were asked to use their middle and index finger of their left hand to press a left or right button. The assigned buttons for "yes" or "no" responses were counterbalanced over participants. Presentation Software (Neurobehavioral Systems, Albany, CA) was used to present the stimuli and to record the responses.

Ongoing brain activity was recorded when participants were performing the task (sampling rate 1200Hz) using a whole-head MEG system with 275 axial gradiometers (VSM/CTF systems, Port Coquitlam, British Colombia, Canada). Head localization was done at the fiducials (nasion, left and right ear canals). A practice section with 32 trials was performed prior the actual experimental phase in order to make sure that the participants understood the task. Afterward, the participants were instructed to sit in a comfortable position which could minimize any movement. Once they were ready, the experimenter initiated the head localization and the data acquisition.

3. Results

Experiment 1

We measured reaction time from the onset of target characters and error rate of the lexical decisions to investigate how functional the radicals are to the processing of the whole character. For the analysis of the existing characters, error trials were excluded.

Pre-exposure of a radical (*M* = 576, *SD* = 186) facilitated the reaction to the lexical decision task compared with a non-functional baseline headstart (*M* = 589, *SD* = 168), (*t*(2408) = 1.70, *p* < .05 (one-tailed)). The main headstart effect suggests that the pre-exposure of radicals facilitates the lexical decision task. In order to further examine the direction of the effects, we split up the data for SP and PS structures. That is because SP character are the most dominate type of phonograms in written Chinese language. We carried out a linear mixed-effect regression analysis, with participants and characters as random factors, on the log RT's of the correct responses for existing SP characters, as predictor types of headstart and the score of familiarity rating. The effect of rating was highly significant: *ß* = -0.04, *t*(1215) = -4.1, *p* < .0005 (one-tailed), ie. the more familiar the readers rated the characters offline, the shorter the reaction time was. The effect of types of headstart to the SP characters is approaching significant for semantic radicals: *ß* = -.025, *t*(1215) = -1.60, *p* < .055 (one-tailed). For phonetic radicals, the headstart effect is non-significant: *ß* = -.018, *t*(1215) = -1.14, *p* < .10. For the PS structure, the rating also has an effect on recognition task. The higher the familiarity rating was, the shorter the reaction time was (*ß* = -0.02, *t*(1241) = -1.90, *p* < .05). The effect of types of headstart to was highly significant for phonetic radicals: *ß* = -.061, *t*(1241) = -4.06, *p* < .001 (one-tailed). For semantic radicals, the headstart effect was non-significant: *ß* = -0.016, *t*(1241) = -1.09, *p* < .14 (one-tailed). The participants responded faster when seeing S headstart for recognizing the SP characters whereas they were faster when seeing the P headstart for recognizing the PS characters.

To test if there was an interaction between character types (SP vs. PS) and the types of headstart (semantic vs. phonetic), we carried out a linear mixed-effect regression analysis on the combined dataset of SP and PS structures. We found that there is a marginally significant interaction between the character types and the types of headstart (*F*(2, 2456)) = 2.6, *p* < .07), suggesting that a semantic headstart is more helpful for processing a SP character while a phonetic headstart is more useful for processing a PS character.

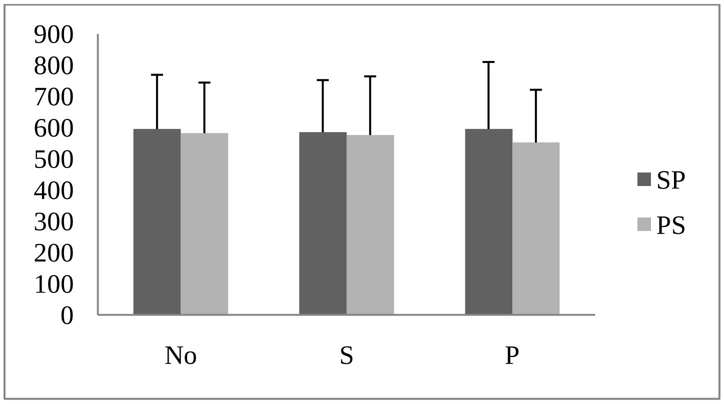

Figure 2. Interaction effect between character structures (SP/PS) and types of headstart (No/S/P) in Experiment 1. The numbers are the reaction time in millisecond (ms).

Experiment 2

Behavioral result from the MEG recordings

The same measure of reaction time as in Experiment 1 was taken, including the correct response for the real character trials. The reaction times during the MEG recordings were approximately 100 ms longer than during Experiment 1 which might result from an unfamiliar testing environment where the participants were settled in a magnetic shielded room, alone. Additionally, the screen resolution and visibility were lower in the projected screen in the MSR. Despite these issues we successfully replicated that the headstart significantly facilitates the lexical decision task. The participants responded faster with the presentation of a headstart ($t(12) = -2.64$, $p < .05$). For effect of types of headstart of the SP characters was significant for both semantic radicals ($t(12) = 2.25$, $p < .05$) and marginally significant for phonetic radicals ($t(12) = 2.04$, $p = .06$). For effect of types of headstart of the PS characters was significant for phonetic radicals ($t(12) = 3.09$, $p < .01$), but not for semantic radicals ($t(12) = 0.45$, $p = .66$). We found that the participants responded faster when they were pre-exposed with the headstarts than without.

A two-way ANOVA was used to test whether there is an interaction between character structures and types of headstart. The result shows that we also replicate such an interaction effect ($F(2,24)=0.28$, $p=.05$). The phonetic radical is more helpful in the processing of a PS character. However, the pattern of SP character deviates from what was found in Experiment 1. The semantic headstart was more helpful than the phonetic headstart in Experiment 1 while both types of headstarts facilitate the performance behaviorally in Experiment 2. The possible reason will be discussed in the Discussion section.

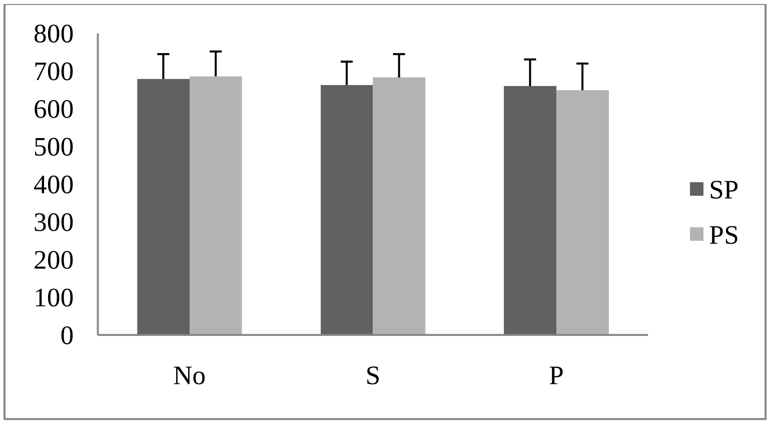

Figure 3. Interaction effect between character structures (SP/PS) and types of headstart (No/S/P) in Experiment 2. The numbers are the reaction time in millisecond (ms).

The analysis of MEG signals

Combined conditions

We first combined all conditions to identify the sensors of of interest. Figure 4A shows the relative changes of power from 200 ms prestimulus to 600 ms post stimulus. This topography detected the induced gamma synchronization mainly over posterior region and some sensors above. Figure 4B shows the TFRs over several sensors at the posterior area. Based on the TFRs, we identified the frequency ranges from around 70 Hz up to 100 Hz for further analysis. Figure 4C shows the changes of induced gamma band activity over the time. This plot shows a 20% changes of gamma band power. The headstart was presented at time -100 ms. The target stimuli were presented at 0 ms. The plot shows that induced gamma turns positively at time t = 0 ms and increased from 100 ms onwards over the posterior region. The gamma power is sustained up to 600 ms poststimulus.

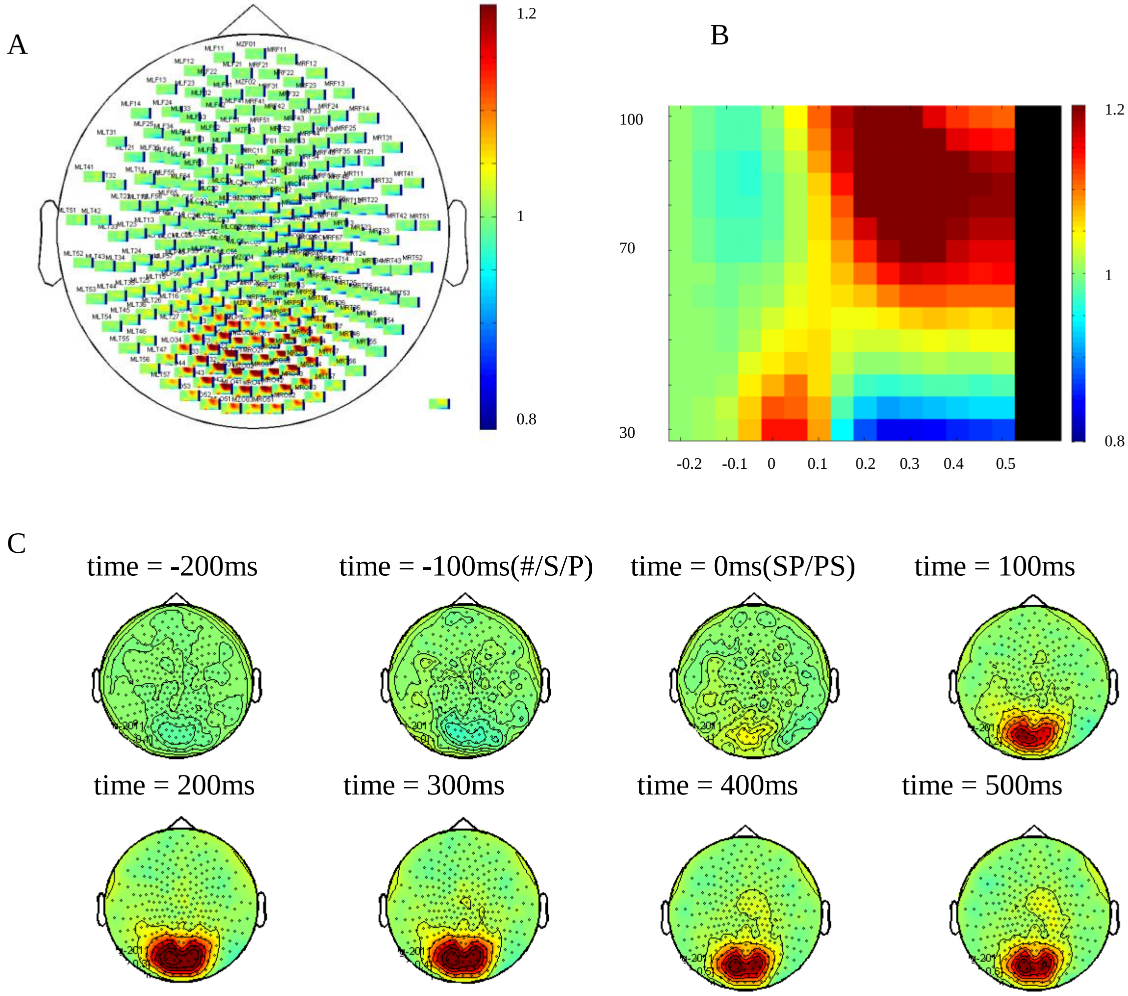

Figure 4. No-headstart condition and headstart condition combined: A) Topography of induced gamma (30~100 Hz), time = -200~600 ms; B) TFRs of induced gamma power over 19 posterior sensors; C) Topography over time of induced gamma (70~100 Hz), time: -200~600 ms, 100 ms per topography.

Contrasting conditions

According to the TFRs of the combined conditions, we identified the time, frequency and sensors of interest for temporal and posterior sites respectively. For the temporal area, 12 sensors were selected from the time window -50 ms to 50 ms, 70 to 100 Hz. The mean over sensors, time window, and frequency range for each participant was then calculated separately for headstart and no-headstart. A pair-wise t-test was used to compare the two conditions. We found no difference between the induced gamma power at the temporal area ($t(12) = 1.03$). Next, we selected the time window from 200 ms to 500 ms post-stimulus, 70 to 100 Hz, and 19 sensors on the posterior site. The mean over sensors, time window, and frequency range for each participant was then calculated separately for headstart and no-headstart as what we did for the temporal area. The subtraction of power spectra are plotted (no-headstart minus headstart conditions). Figure 5A shows that the contrast can be identified at the posterior area and some more anterior sensors. Figure 5B illustrates the TFRs of the contrasts between conditions. Figure 5C shows the changes over time. We can identify a clear region of activity at the posterior area after 200 ms poststimulus.

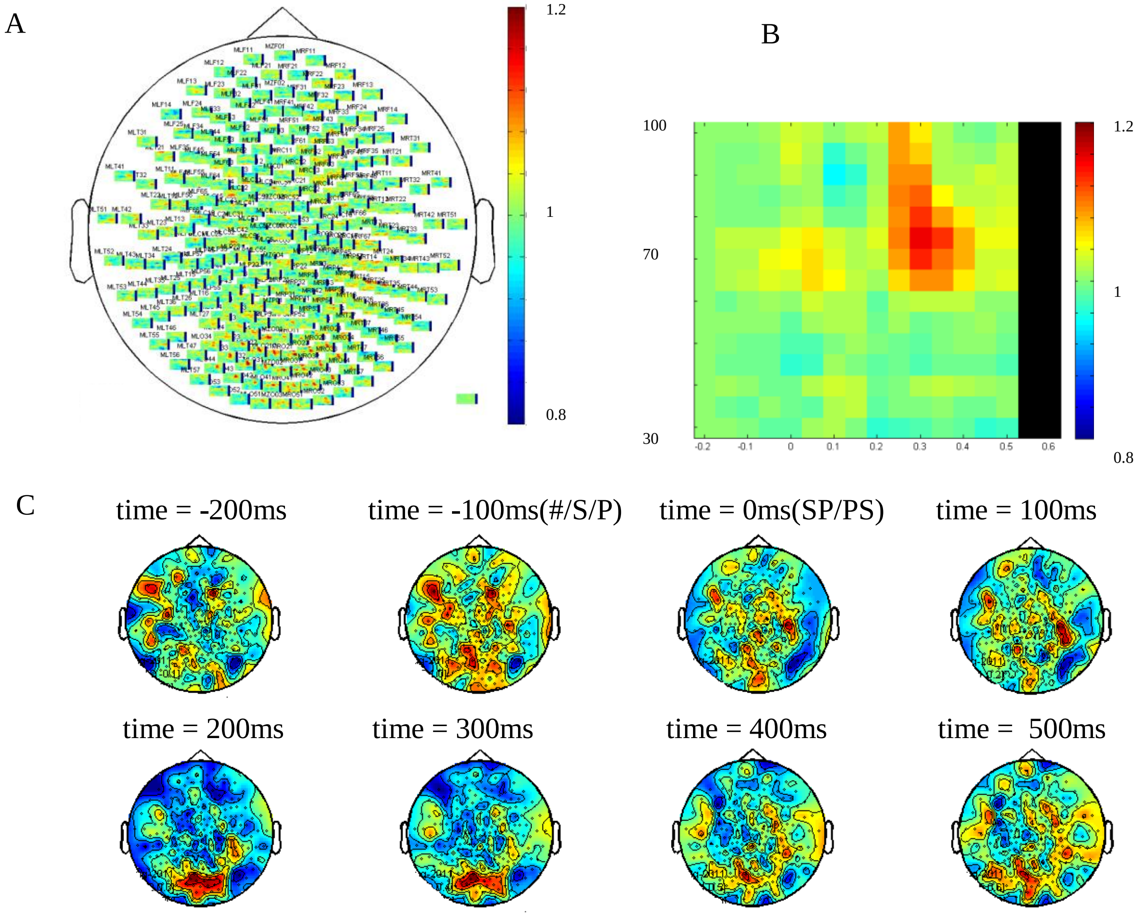

Figure 5. Contrast between no-headstart condition and headstart condition: A) Topography of induced gamma (30~100 Hz), time = -200~600 ms; B) TFRs of induced gamma power over 19 posterior sensors; C) Topography over time of induced gamma (70~100 Hz), time: -200~600 ms, 100 ms per topography.

We compared the mean of induced gamma activity between the two conditions by a pair-wise t-test. The amplitude of gamma band synchronization was stronger for the no-headstart condition than for the headstart condition (Figure 6).

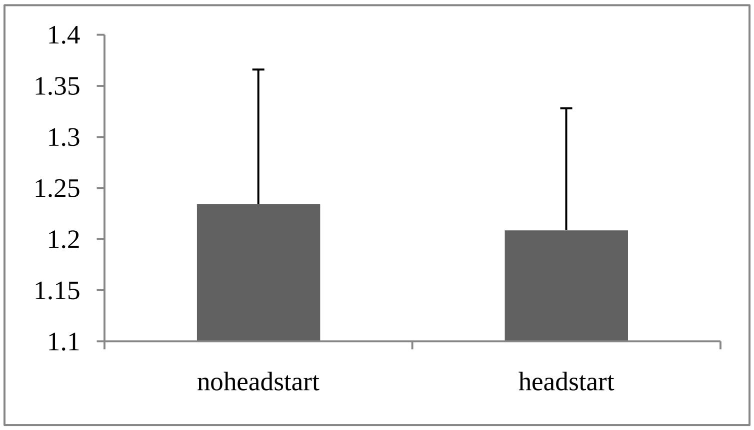

Figure 6. Relative gamma power changes over 19 sensors (time = 200~500 ms; 70~100 Hz) at the posterior area shows a main headstart effect (*t*(12)= -4.09, *p* <.01).

In order to further explore, we regrouped trials based on their character structures and headstart category. We calculated the mean based on the same sensors, time and frequency as we selected above. As what we did for the behavioural result, a two-way ANOVA was applied to examine the interaction effect between character structures and types of headstart which turned to be insignificant (*F*(2,24)=0.28, *p*=.76). To summarize, the induced gamma power was not modulated by the interaction between different types of character structure and types of headstart.

Finally, we tested whether the change of gamma power between conditions and the reaction time were correlated on an individual bases. A normalized reaction time (RT) between the two conditions (headstart vs. no-headstart) was calculated for each participant as

$$RT_{normalized} = (RT_{noheadstart} - RT_{headstart}) / (RT_{noheadstart} + RT_{headstart})$$

and the change of induced gamma power was calculated as the differences between two conditions ($RT_{noheadstart} - RT_{headstart}$). The calculation of the gamma power for the two conditions for each participant was described in the section on contrasting conditions. Pearson’s correlation coefficient was computed and a linear regression analysis was conducted to test the relationship between the neuronal and the behavioural measures for each participant. We tested the correlation between the normalized RT and the posterior gamma power change, the correlation between the normalized RT and the temporal gamma power change, and the correlation between the temporal and the posterior gamma power change. Unfortunately, none of the test was significant. As reported above, the headstart effect was only reflected in the posterior area, but not in the temporal area. We therefore speculate that the noise in the way how we extract the mean for calculating the induced gamma activity at the temporal region made it difficult to further test its correlation with other variables. Based on our results, we did not find individual performance being correlated with the neuronal activity.

4. Discussion

In this study, we found that readers were faster in making a lexical decision when a headstart (semantic or phonetic radicals) was presented 100 ms before the whole character than in the no-headstart condition. This headstart effect suggested that readers processed the radicals as functional information and then processed the whole character. We also found that this headstart effect was reflected in posterior induced gamma activity. When there were no-headstarts, the induced gamma had significantly higher amplitude in the posterior area than when headstarts were presented.

Radical as a sublexical unit in Chinese characters

As stated in the introduction, the pre-exposure of part of the target information (a headstart) could only be useful for recognizing the whole target stimuli when the headstart is functional relevant to the target. In this current study, the headstarts were all legal radicals which are elements of Chinese phonograms. As one would predict, we found that the 100 ms pre-exposition of a radical facilitated the processes of the whole character recognition. The significant headstart effect found behaviourally in both measurements supports the view that radicals in Chinese phonogram are processed in a sublexical level. Meanwhile, we reject a strict view on the whole character recognition hypothesis for Chinese character recognition (Perfetti & Zhang, 1995). In addition, we show that both types of headstart information (i.e. semantic and phonetic radicals) are helpful for recognizing the whole character. Feldman and Siok (1999) showed that the semantic radical is processed during visual Chinese character recognition. They manipulated the semantic relation between the radical and the target. They found that the radicals were served in the sublexical processing of the target and could not be accounted merely as an orthographical recognition. We used a lexical decision task which did not bias towards either semantic or phonological processing and we found that depending on the types of character structures (SP or PS), semantic and phonetic headstarts contribute to the processes differently. Even though the information of the phonetic radical is not always transparent to the pronunciation of the character (Hsiao & Shillcock, 2006), the current study demonstrates that phonetic radicals are still important to identify the whole character, especially for PS characters.

In the behavioral results of both experiments, we have found the interaction effect between types of character structure (SP/ PS) and types of headstart (#/ S/ P). This finding suggests that the two types of headstarts (S/ P) did not help the processing equivalently. For PS characters, the headstart effect was similar in two experiments; namely, the P headstart helped more. As for SP characters, the results were not identical. It was only the S headstart which was helpful in Experiment 1, but in the behavioural result of Experiment 2, both types of headstarts (S/ P) were helpful. This might due to the weak effect for SP character in Experiment 1; thus, the effect for SP character was attenuated by other factors, such as the increasing amount of trial numbers. The significant interaction effect between character structures (SP/ PS) and type of headstart (#/ S/ P) suggests that the readers were benefited differently depending on the specific types of radicals and their character structures. In both cases, the left position seemed to be more important than the unit on the right position. This positional tendency also supports earlier studies (Taft & Zhu, 1997; Taft, et al., 1999) which indicated that the positional information of the characters is crucial for the recognition of the characters. As mentioned above, the ratio of SP and PS characters is 9:1 in the language (Hsiao & Shillcock, 2006). This statistical characteristic of phonogram might contribute to the finding that it took longer for the participants to recognize SP characters than PS characters. We suggested that factors like regularity, consistency of the phonetic radical and combinability of the semantic radical of our stimuli should be taken into account (Hsu, et al., 2011) for understanding the interaction effect between character structures (SP/ PS) and type of headstart (#/ S/ P).

Importantly, this interaction effect illustrates the benefit of headstarts is not just because of visual pattern repetition. The effect would have been equivalent if the headstart effect is only resulting from the reoccurrence of the visual pattern. The positional information and the lexical information of the characters would not have been important. The current findings suggest that the radicals in Chinese phonogram play a functional role for visual character recognition. In addition, semantic and phonetic radicals contribute differently to SP or PS phonograms.

Stronger induced gamma in no-headstart condition

The behavioural headstart effect was reflected in the amplitude of induced gamma responses at the posterior area. The posterior gamma power is stronger in no-headstart condition than in headstart condition. Given that the task in this study is a lexical decision task, we expect necessary linguistic processes in order to perform the task. However, we did not find the effect at the medial temporal area. On the other hand, the occipital area is more associated with perceptual processing. The result found in our study indicated that the perceptual system is more engaged when there were no-headstarts while it is less engaged when there were headstarts. This result did not seem intuitively at the first glance because the headstart condition in fact provides more visual input 100 ms before the onset of the target stimuli. In this case, one might predict that more visual input in the headstart condition demanded more computation effort in the posterior area. However, our result showed the effect reversely. We found that the induced gamma activity was stronger in no-headstart condition. We speculate the following two explanations for interpreting the stronger gamma activity found in no-headstart condition than in headstart condition.

Firstly, the weaker gamma oscillatory activity might be resulting from repetition suppression. Conrad, et al. (2007) showed that the amplitude of induced gamma responses was suppressed after presenting the repeated familiar stimuli. One can argue that in this current study the headstart was functioning like a repetition prime providing a part of the visual pattern which pre-cues the target stimuli. In comparison to the no-headstart condition, the pre-exposing radicals in headstart condition appeared 100 ms extra on the display. This 100 ms headstart was known for 100 ms more than in the no-headstart condition within the experimental context for our participants. When this pre-exposure of information was present in the headstart condition, the induced gamma activity was suppressed.

Alternatively, the higher amplitude of induced gamma power in no-headstart condition can be viewed as an index of the neuronal dynamic between the linguistic system and the perceptual system. Wu et al. (2009) showed that the activity of visual areas was modulated by the difficulty of chunk decomposition task in Chinese characters. The suppression of visual input was due to the demand of semantic and perceptual restructuring process. In the current study, the result can then be interpreted as the headstart is already initiated the beginning of the processing 100 ms ahead; thus, in the headstart condition, the visual area was recruited to a lesser extent which was reflected by the weaker induced gamma power. The headstart facilitated the whole reading network which was reflected by the reduced activation in the visual area and (probably also) the posterior linguistic areas (Pugh, et al., 2001; Seghier, et al., 2008). In contrast, in the no-headstart condition, the whole character appeared at once, it demanded a bigger effort for the reading network. The visual system needs to compute harder in order to match the orthographical information and to retrieve the information from its mental lexicon (e.g. Prat et al., 2007).

The headstart effect was only found in the posterior area, but not in the temporal area. Therefore, the present results support more the first proposal. However, we still speculate that the effect was probably not only due to visual pattern repetition and the reasons are as following. Firstly, the interaction effect found in the behavioural results showed that the headstart effect was not only resulting from the visual pattern repetition between the headstart and the target stimuli, but also the linguistic factors were involved. We successfully replicated the behavioral results in both experiments. Thus, we were confident about the design and the reliability of the measurement. Some other factors might need to be further taken into account in order to interpret the oscillatory activity in our results.

Secondly, previous studies on the time course of visual language processing suggested that orthographical processing happened at about 170 ms after the onset of the stimuli (Maurer, et al., 2005; Zweig & Pylkknäen, 2009) and the sublexical information was retrieved at about 200 ms after the stimuli (Grainger & Holocomb, 2009). Given that the headstart radicals are sublexical units of the Chinese characters, the effect from the visual information of the headstarts should be processed within 200 ms after the presentation of the headstarts, which would be 100 ms after the target stimuli. Moreover, the induced gamma we found at the posterior area was not only responding to the visual form in early time windows, but also sustained up to 600 ms after the onset of the target stimuli. Thus, we speculate that the repetition suppression proposal cannot fully account for our findings.

Finally, we suggest that even though a headstart share some commonality with a prime in repetition priming effect, they are not entirely driven by the same mechanism. In case of a prime, participants are exposed to two different kinds of items at the same position on the screen at different time points. The prime is often overwritten by the target (i.e. repetition priming). For instance, the masked priming paradigm presents first a 500 ms mask (#####) followed by a 50 ms prime (horse) a brief interval filled with a blank or a mask, and then a 500 ms target (HOUSE) (Forster & Davis, 1984). The visual information on the display has been changed each time when there is a new item presented. In contrast to a prime, the headstart in this study stayed at the same position and 100 ms later the target appeared beside it. The visual effect of the headstarts is distinct from other types of primes. In addition, given that the headstart is actually a functional linguistic sublexical unit, readers can start the processing already when they see the headstart. The time interval for our headstart is rather long in comparison to a prime and there is no interval between the presentation of the headstart and the target character. We therefore suggest that the headstarts cannot completely be accounted as visual repetition to the target characters.

We suggest that the headstarts in our study were more similar to a foregoing cue used in word-stem completion task. In a word-stem completion task, the participant was presented by part of the word and was asked to complete the whole word. For instance, they might see *bal*---- and they had to fill in the missing letters. In the current study, participant was not asked to complete the character on their own. So it was only the attempt of completing the whole character which was similar to the word-stem completion task. The task we used was a lexical decision task which participant was asked implicitly to retrieve information from their long-term lexical knowledge. Anderson (2009) referred to tasks like the word-stem completion and lexicon decision task “foregoing tests” whereas the “repetition priming” was another distinct phenomenon.

Although the main headstart effect was reflected in the amplitude of induced gamma activity at the posterior area, the effect was not found at the left temporal area. On the other hand, we have found the interaction effect between character structures (SP/ PS) and types of headstart (#/ S/ P) behaviorally in both experiments which suggests that the headstart effect was not only due to visual pattern repetition. Nevertheless, this interaction effect was not reflected in the power of induced gamma synchronization. The result so far in this study can only support the view that the weaker induced gamma response in headstart condition can be explained as a repetition suppression of the re-presentation of the radicals. However, for several reasons stated above, further analysis is necessary to better understand the effect reported in this study. For instance, we could further analyse the oscillatory activity in respect of the pseudocharacters. In the case of pseudocharacters, the headstart should be a visual repetition to the target pseudocharacters. We would expect to find distinct neuronal activity for identifying pseudocharacters from real characters. If we could show that the modulation was specific to processing real characters, there will be more support for the linguistic-perceptual network proposal.

In conclusion, our findings suggest that radicals are functional units in recognizing a Chinese phonogram. Additionally, the benefit from a 100 ms headstart of a radical is reflected in neuronal oscillatory activity in gamma frequency band at the posterior area between 200 ms to 500 ms after the onset of the whole character presentation. Further analysis is necessary for determining the functional role of induced gamma activity in computing headstart information for later retrieving lexical information from long-term memory.

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