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Research Report

A TMS examination of semantic radical combinability effects in Chinese character recognition

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ABSTRACT

The proposal of human foveal splitting assumes a vertical meridian split in the foveal representation and the consequent contralateral projection of information in the two hemifields to the two hemispheres and has been shown to have important implications for visual word recognition. According to this assumption, in Chinese character recognition, the two halves of a centrally fixated character may be initially projected to and processed in different hemispheres. Here, we describe a repetitive transcranial magnetic stimulation (rTMS) investigation of hemispheric processing in Chinese character recognition, through examining semantic radical combinability effects in a character semantic judgment task. The materials used were a dominant type of Chinese character which consists of a semantic radical on the left and a phonetic radical on the right. Thus, according to the split fovea assumption, the semantic and phonetic radicals are initially projected to and processed in the right hemisphere and the left hemisphere, respectively. We show that rTMS over the left occipital cortex impaired the facilitation of semantic radicals with large combinability, whereas right occipital rTMS did not. This interaction between stimulation site and radical combinability reveals a flexible division of labor between the hemispheres in Chinese character recognition, with each hemisphere responding optimally to the information in the contralateral visual hemifield to which it has direct access. The results are also consistent with the split fovea claim, suggesting functional foveal splitting as a universal processing constraint in reading.

1. Introduction

In Chinese orthography, the dominant category, the phonetic compound, comprises about 81% of the 7000 frequent characters in a Chinese dictionary (Li and Kang, 1993). These phonetic compound characters have a distinct composition in which a semantic radical signifies the meaning of the character and a phonetic radical contains information about the character's pronunciation. The extent to which a radical's ease of combinability helps character recognition has long been a controversial issue. According to Feldman and Siok (1999), a radical's combinability is the number of combinations that it can enter into to form characters. Early research on this issue was focused on how radical combinability helps character decisions. Nevertheless, the results obtained in previous studies were incon-

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sistent (Chen and Weekes, 2004; Feldman and Siok, 1999; Taft and Zhu, 1997).

The inconsistent results obtained in the previous studies reflect the complexity of the processes involved in character decision tasks (Hoosain, 1991; Hsiao et al., submitted for publication; Tan and Perfetti, 1998). In contrast, studies concerning the influence of semantic radical combinability on semantic judgment tasks have exhibited consistent results. Chen and Weekes (2004) showed that large semantic radical combinability facilitated character semantic categorization. Hsiao et al. (submitted for publication) also reported the same effect in a character semantic transparency judgment task. In their study, participants were asked to judge whether a presented character was semantically directly related to its semantic radical (transparent) or not (opaque), according to its most frequent meaning. Their materials consisted of phonetic compounds that have the prevailing left–right structure in which the semantic radical appears on the left and the phonetic radical on the right (SP characters).[1] They also used lateralized parafoveal cues to examine semantic information distribution within the SP characters with different semantic radical combinability. Their results showed an interaction between cue position (left vs. right) and semantic radical combinability (large vs. small): compared with a right cue, a left cue facilitated semantic judgments of characters containing a semantic radical with small combinability, but not large combinability. They argued that semantic radicals with small combinability are more informative in determining character meaning than those with large combinability since there are only a small number of characters sharing the same semantic radical. In contrast, semantic radicals with large combinability are less useful in determining character meaning, and hence, in these cases, the phonetic radicals are relatively more informative in retrieving character meaning. Here, we report a further investigation of Chinese semantic radical combinability effects in character level semantic processing through repetitive transcranial magnetic stimulation (rTMS), utilizing the distinct structure of SP characters to examine the implications of foveal splitting for hemispheric processing in Chinese character reading.

In recent years, there has been converging evidence from human studies, suggesting at least a functional splitting of the human foveal representation. The evidence ranges from various visual hemifield studies of commissurotomy patients (Fendrich and Gazzaniga, 1989; Fendrich et al., 1996; Harvey, 1978) to neuroimaging studies (Gray et al., 1997; Portin and Hari, 1999). Foveal splitting has been shown to have important implications for visual word recognition (Brysbaert, 2004; Shillcock et al., 2000). A number of studies have examined previously reported visual field differences with foveally presented lexical stimuli. The general finding has been that the different processing styles of the two hemispheres have contralateral influences on responses driven by the first and last halves of the stimuli. The effects being examined in these studies included the optimal viewing position effect (Brysbaert, 1994), the word length effect (Lavidor et al., 2001), case alternation effects (Ellis et al., 2005) and the orthographic neighborhood effect (Lavidor et al., 2004; Lavidor and Walsh, 2003). All these studies have supported the split fovea claim.

In the current study, we propose an examination of hemispheric processing in Chinese character recognition based on the split fovea claim. The materials we used were Chinese SP characters, which consist of a semantic radical on the left and a phonetic radical on the right. The SP structure is the most typical structure of Chinese orthography and hence is important for the understanding of cognitive processes involved in character recognition.[2] Furthermore, the radicals usually can be standalone characters and can be considered as semantic elements (i.e., morphemes). Chinese SP characters hence provide an important opportunity to examine the coordination between different morphemes in character recognition and its interaction with the split fovea. Specifically, if foveal vision is split, when an SP character is centrally presented with the fixation between its semantic and phonetic radicals, the phonetic radical would be initially projected to the left hemisphere (LH), whereas the semantic radical would be initially projected to the right hemisphere (RH). The assumption that the initial projection of the two types of radical is to separate hemispheres enables us to predict that differential hemispheric processing will occur for characters with different semantic radical combinability.

The approach we adopted was to apply rTMS over the left and right occipital cortex. Several types of visual recognition task have been disrupted by TMS applied over the occipital pole at various delays from the letter or the word presentation onset. For example, single letter identification was impaired when TMS was applied over the striate visual cortex (Corthout et al., 1999) and identification of briefly presented letter trigrams was significantly impaired when the visual stimulus preceded the occipital magnetic stimulus by 40–120 ms (Amassian et al., 1989; Beckers and Homberg, 1991). Lavidor et al. (2003) showed that applying rTMS over the right occipital cortex significantly inhibited lexical decision performance to foveal targets in the left visual field (LVF), but not to those in the right visual field (RVF). The complementary pattern was obtained when stimulating the left occipital cortex. Potts et al. (1998) tracked TMS sites with magnetic resonance imaging (MRI) and concluded that TMS-induced visual suppression is likely to be due to a focal disruption in the occipital cortex contralateral to the visual suppression effects. Thus, unilateral rTMS over the occipital cortex affects the processing of contralateral foveal targets.

The current study concerns an rTMS examination of the semantic radical combinability effect in Chinese phonetic compound recognition. If the foveal representation is vertically split about fixation, the semantic radical of an SP character will be initially projected to the contralateral RH, and we can apply rTMS to the RH to directly impair the processing of the

[1] These SP characters comprise approximately two-thirds of the phonetic compounds (Hsiao and Shillcock, submitted for publication).

[2] Although the opposite arrangement also exist, e.g., PS characters, they comprise only 5% of the frequency characters. In the current study, we were examining the interaction between the split fovea claim and the normative processing of phonetic compounds, i.e., SP structure. Whether or not PS characters are processed comparably to SP but reversed requires further separate examination.

semantic radical. In contrast, rTMS to the LH should directly affect the processing of the phonetic radical, which is initially projected to the LH. As noted earlier, the semantic radical of characters with small semantic radical combinability is relatively informative in determining character meaning, whereas, for characters with large semantic radical combinability, it is the phonetic radical which is relatively more informative (Hsiao et al., submitted for publication). We thus predict that unilateral rTMS will have different effects on the semantic processing of characters with large and small semantic radical combinability; more specifically, characters with small semantic radical combinability may be more vulnerable to rTMS to the right occipital cortex, whereas those with large semantic radical combinability may be more vulnerable to rTMS to the left. The semantic transparency judgment task requires participants to access the meaning of the character. Thus, there may be departures from the results obtained from the nearest alphabetic-language analogue to this experiment, Lavidor and Walsh's (2003) lexical decision-based rTMS experiment with the central presentation of high vs. low lead neighborhood words in English. We will return to this issue in the Discussion section.

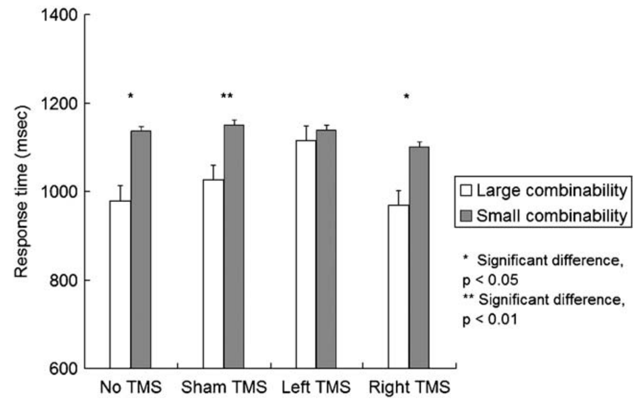

Fig. 1 – Error bar plots of the mean response times as a function of semantic radical combinability in different TMS conditions. The error bars show standard errors.

2. Results

All participants performed well in the symbol judgment task, with accuracy larger than 95% and hence no one was removed from the analyses. Table 1 summarizes the participants' mean correct response times, standard errors and mean accuracies as a function of radical combinability, character type and TMS condition. Repeated measures analysis of variance was carried out. For response times, there was a strong main effect of combinability ($F(1,7) = 16.290$, $P = 0.005$), with characters with large semantic radical combinability responded to faster than those with small semantic radical combinability, and a strong main effect of character transparency ($F(1,7) = 38.557$, $P < 0.001$), with transparent characters responded to faster than opaque characters. A significant interaction between TMS conditions and combinability was also observed ($F(3,21) = 4.690$, $P < 0.05$). As shown in Fig. 1, the combinability effect was significant in the no TMS condition ($F(1,7) = 10.583$, $P < 0.05$), the sham TMS condition ($F(1,7) = 17.876$, $P < 0.01$), and the right TMS condition ($F(1,7) = 10.328$, $P < 0.05$), but not the left TMS condition ($F(1,7) = 2.945$, n.s.). For characters with large semantic radical combinability, the left TMS condition significantly increased the response time when compared with the other conditions ($F(3,21) = 3.805$, $P < 0.05$). In contrast, the four TMS conditions did not have significant effects on characters with small semantic radical combinability ($F(3,21) = 0.365$, n.s.).

Table 1 – Summary of the mean response times, standard errors and mean accuracies as a function of radical combinability, character type and TMS condition

	Transparent		Opaque	
	Large combinability	Small combinability	Large combinability	Small combinability
No TMS				
Mean RT	854	1032	1119	1261
Standard error	46	80	79	111
Mean accuracy	95%	90%	86%	80%
Sham TMS				
Mean RT	931	1032	1133	1284
Standard error	68	75	56	104
Mean accuracy	94%	88%	91%	81%
Left TMS				
Mean RT	1024	1007	1218	1287
Standard error	97	85	83	117
Mean accuracy	91%	88%	84%	83%
Right TMS				
Mean RT	850	975	1102	1238
Standard error	58	69	96	97
Mean accuracy	93%	89%	89%	84%

In a separate analysis, the interaction between rTMS site (left vs. right) and semantic radical combinability was also significant ($F(1,7) = 6.109$, $P < 0.05$; see Fig. 1); when compared with the right TMS condition, left rTMS stimulation slowed participants' response time to characters with large semantic radical combinability ($F(1,7) = 20.372$, $P < 0.01$), and hence eliminated the combinability effect. In contrast, the combinability effect was not affected when right rTMS stimulation was applied.

For the accuracy data, a significant main effect of combinability ($F(1,7) = 28.167$, $P = 0.001$) and a significant main effect of character transparency ($F(1,7) = 7.691$, $P < 0.05$) were observed; transparent characters and characters containing semantic radicals with high combinability were responded to with greater accuracy. The interaction between TMS condition and combinability was not significant ($F(3,21) = 0.309$, n.s.) neither was the interaction between rTMS stimulation site (left vs. right) and combinability ($F(1,7) = 0.111$, n.s.).

Accuracy in reporting the small symbols/numbers reached a mean accuracy of 99.25%. Hence, the stimuli were properly foveated and the possibility that the current results reflected any systematic shift or bias in fixation can be precluded.

3. Discussion

In the current study, we have used TMS to examine the interaction between the information structure of Chinese SP characters, reflected in their semantic radical combinability, and the two hemispheres in a character semantic judgment task. We have demonstrated significant facilitatory effects of large semantic radical combinability and character transparency. The results showing these effects replicate previous findings reported by Chen and Weekes (2004) and Hsiao et al. (submitted for publication). As discussed in Hsiao et al., the semantic radical combinability facilitatory effect can be interpreted as being equivalent to the neighborhood effect in English visual word recognition (Lavidor et al., 2004; Lavidor and Walsh, 2003) (cf. Andrews, 1997), in which the recognition of centrally presented words with many "lead neighbors" (i.e., many words sharing the same initial letters) was facilitated compared with words with few lead neighbors. The facilitatory effects observed in both English word and Chinese character recognition have been restricted to the LVF/RH. How far can this comparison with the neighborhood effect in English be retained, in light of the current data?

In the rTMS examination of the semantic radical combinability effect, we applied rTMS over the left or the right occipital cortex to disrupt the visual input into the two hemispheres and obtained a significant interaction between rTMS stimulation site (left vs. right) and semantic radical combinability (large vs. small). Compared with the right TMS condition, applying rTMS over the left occipital cortex significantly slowed the response time to characters with large semantic radical combinability, and hence eliminated the facilitatory effect of large semantic radical combinability. This result seems to be contradictory to the research on lexical processing in alphabetic languages, which suggested that impairing right, not left, occipital cortex should cancel the combinability effect by impairing the representation of the semantic radical in the LVF/RH. Below, we will argue that all of the relevant studies can be fitted coherently within a split fovea account and that the current data are a consequence of a division of labor between the two hemispheres, with each responding optimally to the information in the contralateral visual hemifield.

First, we consider the relationship between the visual lexical decision task used for alphabetic stimuli and the semantic transparency judgment task used in the current experiment. The elimination of the lead neighborhood effect in English lexical decisions by rTMS over the RH (Lavidor and Walsh, 2003) is best conceived of in terms of the operation of a mechanism specific to lexical decision tasks. Grainger and Jacobs (1996) proposed that words with a large neighborhood cause greater global lexical activity, which facilitates positive lexical decisions. This account of the neighborhood effect was supported in a further study, using event-related brain potentials (ERP), showing that a larger N400 component was observed for large neighborhood words compared with small neighborhood words (Holcomb et al., 2002). The lead neighborhood effect in lexical decisions thus can be explained by a larger global lexical activation in the RH for large lead neighborhood words compared with small lead neighborhood words. Applying rTMS over the right occipital cortex disrupts the input to this global lexical activation and destroys the lead neighborhood effect. Note, however, that similar behavior could stem from global semantic activation in the RH. Holcomb et al. (2002) observed the same ERP data for nonwords, indicating to Holcomb et al. a relatively early, prelexical stage of processing. But note that these data are also interpretable as the result of semantic incongruity between the simultaneously activated meanings of all of the words beginning with the left part of the fixated word. It could be that the neighborhood effect is driven by larger global semantic activation in the RH, based on the left part of the fixated word or nonword; larger global semantic activation would facilitate a positive lexical decision but hinder a negative one. Thus, rTMS over the right occipital cortex would remove the neighborhood effect by impairing the input to measures of global lexical activation and/or global semantic activation.

In contrast to the lexical decision task, the semantic transparency judgment task requires full access to the unique meaning of the particular character; the participant must decide if the meaning of the whole character is related to the meaning of the semantic radical. Accessing the meaning of the whole character means taking into account the implications of the phonetic radical, which raises the issue of the difference in information structure of English words and Chinese characters. In English words, there is typically more information on the left of the word (Bryden et al., 1990), but, in Chinese characters, there is more information on the right of an SP phonetic compound character (Hsiao and Shillcock, submitted for publication). Hence, critical processing of the RVF/LH input must occur, and rTMS applied to the left occipital cortex disrupts the input to this processing.

When reading an SP character with large semantic radical combinability, the expectation is that more information in the character resides on the right: if only the left semantic radical was available, the whole character could be any of a range of characters and meanings and the right phonetic radical would therefore be more informative in determining the unique meaning of the whole character. Applying rTMS to the LH significantly slowed the response time to these characters in the semantic judgment task, confirming that the information relevant to the semantic judgment is skewed to the right radical, which is initially projected to the LH.

For characters with small semantic radical combinability, the semantic radical on the left is more informative in determining the character meaning than is the semantic radical of characters with large semantic radical combinability. Applying rTMS over the LH did not significantly increase participants' response time to those characters with small combinability semantic radicals since reliable semantic information was still available from the semantic radical projected to the RH. In other words, access to the meaning of a character with a small combinability semantic radical is achieved by a relatively equal reliance on information on the left and right of the character; for a character with a large combinability semantic radical, the reliance is more skewed to the information on the right of the character.[3]

We do not see a combinability effect confined to a particular place in one or other hemisphere; instead, we see a flexible division of labor between the hemispheres, with each responding optimally to the information in the visual hemifield to which it has direct access. As discussed in Hsiao et al. (submitted for publication), this facilitation of large semantic radical combinability in the semantic judgments may have resulted from the match between the information structure of the SP characters with large semantic radical combinability and the distinction of coarse/fine semantic coding between the RH and LH (Beeman and Chiarello, 1998). According to the split fovea claim, when an SP character is centrally fixated, its semantic radical is initially projected to and processed in the RH, which weakly activates coarse-coded, largely overlapped semantic fields of all related meanings of the characters with the same semantic radical. In contrast, the phonetic radical is initially projected to and processed in the LH; the LH consequently strongly activates fine-coded, narrow semantic fields of the phonetic radical, which is also the relatively more informative part of a character in determining the exact meaning of the character compared with the semantic radical. Thus, the information structure of the characters with large semantic radical combinability matches better with this distinction between the two hemispheres than that of the characters with small semantic radical combinability; consequently, the semantic processing of the former characters is facilitated.[4]

A similar phenomenon has also been reported in English lexical decision tasks: for centrally presented words, the facilitatory effect of large neighborhood size in lexical decisions only applies to lead neighborhoods, but not end neighborhoods (Lavidor et al., 2004). This phenomenon can also be construed as a better fit of the information structure of words with a large lead neighborhood size with the processing style of the two hemispheres, compared with words with a small lead neighborhood size. In contrast, words with a large end neighborhood size do not have the facilitation because word codas are initially projected to the LH, whose processing does not benefit from a large end neighborhood size due to its fine-coding processing nature. Similar phenomena may also be observed in semantic categorizations of English words. According to the ERP study by Holcomb et al. (2002), the larger N400 amplitude that was observed for large neighborhood words than small neighborhood words in lexical decisions was also observed in a semantic categorization task.

Another example of the interaction between functional brain structure and the information structure of words comes from an English word naming experiment. Brysbaert (1994) reported that the word-beginning superiority effect, that is, words are more efficiently processed when being fixated within the beginning half, was larger for participants with LH dominance than for participants with RH dominance. It demonstrated a flexible division of labor between the two hemispheres in processing centrally presented words (note that aspects of the RH/LH coarse/fine distinction may be reversed in lefthanders; Mevorach et al., 2005). Thus, this interaction between the hemispheres and information structure of words has been shown to be a universal phenomenon existing in the processing of orthographically different languages (see also Deutsch and Rayner, 1999; Farid and Grainger, 1996).

Differences between Lavidor and Walsh's (2003) rTMS study and the current study in terms of cognitive processes involved in different tasks are crucial to drawing these TMS data together, and both studies are accommodated consistently within the split fovea account. In both studies, the rTMS was applied to the occipital cortex, responsible for the early perceptual processing of the character or word. The rTMS over the right occipital cortex destroyed the facilitatory effect of large lead neighborhood size in English lexical decision tasks because it impaired the beginning segment of the input word,

[3] It might be argued that the combinability effect observed in the current study may be caused by the difference between the visual complexity of the semantic radicals with large and small combinability since the radicals with small combinability tended to have more strokes than those with large combinability. We argue that it is unlikely since there has been evidence showing that the smallest functional processing units of Chinese character recognition are the well-defined stoke patterns which repeatedly appear in Chinese characters, instead of strokes (Chen et al., 1996). Although the radicals with small combinability tended to have more strokes, most of them could still be considered as stroke patterns that were as well-defined as those with large combinability. Furthermore, this combinability effect was observed in simplified Chinese scripts (Chen and Weekes, 2004), in which the difference in visual complexity is less salient.

[4] Feldman and Siok (1999) reported that the facilitation of large semantic radical combinability was restricted to the semantic radicals on the left (i.e., SP characters) as opposed to the right (i.e., PS characters). This result is consistent with the claim here: PS characters do not have a good fit with the coarse/fine coding distinction between the two hemispheres and hence do not show facilitation, albeit the task they adopted was a character decision task.

which was important for the RH to accumulate global lexical activation; in contrast, the rTMS over the left occipital cortex selectively impaired the processing of characters with large semantic radical combinability in Chinese semantic transparent judgments because the semantic radical, which was projected to the RH, provided less semantic information about the exact character meaning than one with small combinability when the perceptual input to the LH (i.e., the phonetic radical) was impaired.

In summary, in this rTMS examination of semantic radical combinability effects in Chinese character recognition, we have replicated previous findings about the facilitatory effect of semantic radicals with large combinability in a character semantic transparency judgment task. We also have obtained a significant interaction between rTMS stimulation site (left vs. right) and semantic radical combinability (large vs. small). This result was consistent with the claims regarding human foveal splitting through examining semantic processing of Chinese orthography and has suggested functional foveal splitting as a universal language processing phenomenon in reading. Furthermore, by drawing together the data from the TMS examinations of the lead neighborhood effect in English lexical decisions and the combinability effect in Chinese character semantic judgments, we have discussed different cognitive processes involved in the two tasks and shown that both studies can be accommodated consistently within the split fovea account. Applying rTMS over the occipital cortex disrupts visual character/word recognition most when it is applied to where the most informative part of the character/word is projected in respect of the task. For the English lexical decision task, it is the lead half of the word presented in the LVF/RH; for the Chinese character semantic judgment task, it is the right radical projected to the RVF/LH. The interaction between stimulation site and the combinability/neighborhood effect in both studies reveals a flexible division of labor between the two hemispheres, with each hemisphere responding optimally to the information in its contralateral visual hemifield. Thus, we have gone some way towards reducing phenomena reported in visual word recognition – neighborhood effects and combinability effects – to a clearer relationship between the brain and the distribution of information in the outside world.

4. Experimental procedures

4.1. *Design*

The experiment included three within-subject variables: character transparency (transparent vs. opaque), semantic radical combinability (large vs. small) and TMS condition (no TMS, sham TMS, TMS over the left occipital cortex (left TMS) and TMS over the right occipital cortex (right TMS)). In the no TMS condition, there was no coil placed onto the participant and no simulation was given. In the sham TMS condition, we put the edge of the coil perpendicular to the head; in other words, the magnetic field produced by the coil was parallel to the surface of the head, and hence no magnetic field stimulation was transferred to the cortex. This technique was also used in some previous studies (Chiang and Lavidor, 2005; Lavidor and Walsh, 2004; Walsh and Pascual-Leone, 2003). Although the conditions in which TMS was applied to different sites provide the best controls for each other, the sham condition was included for completeness. The dependent variables were the correct response time in milliseconds and the response accuracy.

4.2. *Materials*

The materials consisted of 256 Chinese SP characters. Half of the characters were transparent and the other half were opaque. Within both transparent and opaque groups, half of the characters had large semantic radical combinability and half had small semantic radical combinability. All characters were within the medium to high frequency range according to a frequency count study of traditional Chinese character usage reported by Huang (1995); there were no significant frequency differences among the characters in the four experiment conditions ($F(3,252) = 1.12$, n.s.). In order to compare the results of the current study with Hsiao et al. (submitted for publication) and Chen and Weekes' (2004) studies, most characters were selected from their materials (N. B. Chen and Weekes used simplified characters and hence the characters were converted into traditional forms[5]) and the corresponding transparency was adopted. The additional characters were assessed for transparency by a native speaker of Chinese (JHH) according to a traditional Chinese dictionary (Mandarin Promotion Council, 2000). Characters whose transparency was ambiguous, possibly because of more than two high-frequency competing meanings, were excluded from the materials.

Combinability of each character was calculated according to a Chinese phonetic compound database, which contains the 2159 most frequent left–right structured phonetic compounds (Hsiao and Shillcock, submitted for publication). From this database, we selected 11 semantic radicals from those with the largest combinability and 22 semantic radicals from those with the smallest combinability.

The semantic radicals with large combinability were: 扌 (手), 亻 (人), 口, 忄 (心), 木, 氵 (水), 糸, 月 (肉), 言, 女 and 金. Those with small combinability were: 巾, 弓, 彳, 歹, 牛, 田, 禾, 立, 冫 (冰), 米, 缶, 耳, 貝, 走, 車, 酉, 革, 食, 馬, 骨, 黑 and 齒. According to the database, all of the semantic radicals in the large combinability group had a combinability greater than 53. In other words, for any given semantic radical in this group, there were more than 53 left–right phonetic compound character types sharing this same semantic radical. In contrast, all of the semantic radicals in the small combinability group had a combinability of less than 27 (Hsiao and Shillcock, submitted for publication). For each semantic radical, the same numbers of transparent and opaque characters that have this given semantic radical were included in the materials. The semantic radicals adopted tended to have low consistency since opaque

[5] The visual complexity (i.e., the number of strokes) of radicals and characters is significantly reduced in simplified characters, but the structure of characters (e.g., SP and PS structures in phonetic compounds) remains the same. Hence, we do not expect that results would be different if simplified characters were used.

characters with a highly consistent semantic radical are rare and it is difficult to allocate the same number of transparent and opaque characters for such semantic radicals.

The experiment was conducted with the Psychology software E-Prime v1.1. A PST serial response box was used to collect the data.

4.3. *Participants*

The participants consisted of four females and four males, all right-handed according to the Edinburgh Handedness Inventory (Oldfield, 1971). They were all international graduate students from Taiwan in London, whose ages ranged from 23 to 35. The mean age of the participants was 27 years and 5 months. Participants volunteered or received a small honorarium for their participation. They were all native Chinese speakers from the same culture (Taiwan) and had similar educational backgrounds. They all had normal or corrected to normal vision.

Each participant was given an information pamphlet explaining the TMS procedure before the experiment and was given at least 24 h after reading the pamphlet to decide whether to participate or not. Before the experiment, all participants were also required to sign a consent form and report absence of any neurological conditions, such as epilepsy, in themselves and their family. This experiment was reviewed and approved in advance by the Joint UCL/UCLH Committees on the Ethics of Human Research.

4.4. *TMS design*

Stimuli were divided evenly into eight blocks of 32 stimuli each. The four different types of characters were evenly distributed in each block. Characters with the same semantic radicals were also evenly distributed in each block; they were prevented from appearing in the same block to avoid any priming effects. During the experiment, each TMS condition (no TMS, sham TMS, left TMS and right TMS) was assigned to two blocks. In each block, the character presentation order was random, and the magnetic stimulation site was fixed. An orthogonal Latin square design was adopted to counterbalance the various block sequences in which different TMS conditions might occur.

During the experiment, binocular vision was used. Characters were all presented in a standard calligraphic font and in the same size. The size of the characters was 1.8 × 1.8 cm, which was about 1° of visual angle, and the viewing distance was 100 cm. These limits were applied to ensure that the stimulus presented fell inside foveal vision.

The magnetic stimulator used was MagStimTM, model Super Rapid with 4 external boosters (maximum output around 2 T). The output pulse was biphasic. A 50-mm figure-of-eight coil was used. The center of the coil, where the two circles meet, was placed onto the stimulation site horizontally, with the two circles to the left and right of the site and the handle pointed vertically. Hence, the current direction was from top to bottom. For each participant, the stimulation sites on the occipital cortex were decided by locating the sites where contralateral stationary phosphenes were elicited by magnetic stimulation. Participants were asked to put on a latex swimming cap so that markers could be fixed on the head. A marker was attached to a reference site which was 2 cm above the upper edge of the inion. The left and right hemispheric stimulation sites were 1.5 cm to the left and right of this reference site, respectively. These primary locations were based on previous studies where stationary phosphenes were reported (Lavidor and Walsh, 2003). After the left and right sites were located, participants were put in the dark and asked to close their eyes, while a single pulse was applied at various intensities, starting from 40% output and increased at an interval of 5% output, until participants reported phosphenes reliably and consistently. Participants were asked to report whether they saw phosphenes and the location of the phosphenes. If any phosphene was identified, stimulation was applied at the same site again with a decreased intensity at an interval of 5% output until the participant was not able to see the phosphenes. A phosphene threshold, which was the lowest stimulation intensity required to elicit phosphenes, was recorded for each participant. If participants did not see phosphenes on the sites, a "win-stay/lose-shift" paradigm was conducted in the neighboring area until the phosphene perception sites were located (Ashbridge et al., 1997). Thus, we could ensure that stimulation on the left and right sites would successfully produce disruption to contralateral visual fields. During the experiment, the intensity of magnetic stimulation for each participant was fixed at 90% of his or her phosphene threshold. The frequency of stimulation was 10 Hz, lasting for 500 ms from the onset of the character presentation. These settings and procedures were chosen to match the conditions used in previous rTMS examinations of split foveal processing (Lavidor and Walsh, 2003).

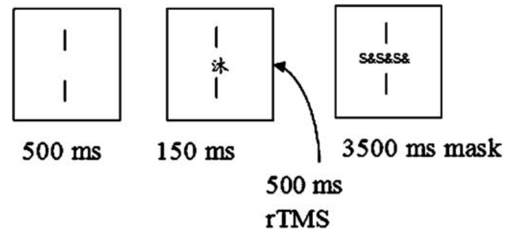

Fig. 2 – Timeline of the experiment.

4.5. *Methods*

Participants were asked to keep their head on a chin rest so that the distance between the screen and the participants' eyes was kept constant. Every participant was presented with all the materials during the experiment, and only saw each character once.

During the experiment, characters were presented one at a time in a random order on the computer screen. After each presentation of a character, participants were asked to press the inner buttons of a response box with four keys with their left and right index fingers simultaneously if the character was a transparent character and press the outer buttons with their left and right middle fingers simultaneously otherwise. They were asked to respond as quickly and accurately as possible by pressing the corresponding buttons. We measured the time difference between the onset of the character presentation and the button response. Each trial started with a 500-ms prompt with two short vertical lines. After that, the target character appeared for 150 ms between the two lines followed by a mask for another 3500 ms while waiting for participants to make a response (see Fig. 2 for the timeline of the experiment). The next cycle began right after the mask presentation.

Participants were asked to fixate the middle of the space between the two short lines all the time during the experiment. This point approximately coincided with the boundary between the phonetic and semantic radicals in each character presentation. Participants could take a break after each block until they were ready to start the next one. Occasionally, a very small symbol was presented between the two short lines and participants were asked to respond "yes" if the symbol was a digit and "no" otherwise. This procedure was to make the participants fixate at the right place (Brysbaert, 1994). Each block contained eight such stimuli. Data from any participant who did not respond to the symbols with an acceptable accuracy was not considered.

Clear instructions were given to each participant before the experiment, including a brief review of the meaning of the semantic radicals used in the materials to make sure that the participants knew the meaning of the radicals before the experiment started. A practice session, which consisted of 20 symbols and 32 characters whose semantic radicals were different from those in the experimental materials, was also provided at the start. Participants had ample opportunity to ask any procedural questions regarding the experiment before the test trials began. The whole experiment lasted approximately 1 h. Each participant completed the experiment in one session; all the participants were run in the same week.

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