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BRIEF REPORT

Spatial Stroop interference occurs in the processing of radicals of ideogrammic compounds

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Abstract In this study, we investigated whether the meanings of radicals are involved in reading ideogrammic compounds in a spatial Stroop task. We found spatial Stroop effects of similar size for the simple characters 上 ("up") and 下 ("down") and for the complex characters 忐 ("nervous") and 忑 ("nervous"), which are ideogrammic compounds containing a radical 上 or 下, in Experiments 1 and 2. In Experiment 3, the spatial Stroop effects were also similar for the simple characters 东 ("east") and 西 ("west") and for the complex characters 陈 ("state") and 洒 ("spray"), which contain 东 and 西 as radicals. This outcome occurred regardless of whether the task was to identify the character (Exps. 1 and 3) or its location (Exp. 2). Thus, the spatial Stroop effect emerges in the processing of radicals just as it does for processing simple characters. This finding suggests that when reading ideogrammic compounds, (a) their radicals' meanings can be processed and (b) ideogrammic compounds have little or no influence on their radicals' semantic processing.

Keywords Chinese character · Radical · Ideogrammic compound · Spatial Stroop effect

A central question in psycholinguistic research concerns the types of information stored and the ways in which information is represented in the mental lexicon. As for the Chinese mental lexicon, researchers have reached a consensus that Chinese characters have representations at a lexical level (Perfetti, Liu, & Tan, 2005; Taft, 2006; Tsang & Chen, 2009). However, whether and how the radicals embedded in complex Chinese characters are represented in the mental lexicon are still matters of debate (e.g., Ding, Peng, & Taft, 2004; Zhou, Peng, Zheng, Su, & Wang, 2013).

Modern Chinese characters are mainly divided into simple and complex characters. *Simple characters* occupy about 5 % of the total characters and have holistic visual patterns that cannot be divided meaningfully into sublexical units, such as 犬 (dog) and 马 (horse); *complex characters* constitute about 95 % of total characters and have two or more radicals (Zhou & Marslen-Wilson, 1999). About 80 % of the complex characters are phonetic compounds consisting of phonetic and semantic radicals, which provide cues to their host characters' pronunciation and meanings, respectively (e.g., Zhou et al., 2013). For example, 妈 ("mother") is constructed from the phonetic radical 马 ("horse") and the semantic radical 女 ("female"). Another 13 % of complex characters are ideogrammic compounds constructed by combining two or more radicals' meanings, and these radicals are unrelated to their host characters in pronunciation. For instance, combining 日 ("sun") and 月 ("moon"), the two natural sources of light, makes 明 ("bright").

Accumulating evidence is suggesting that in the reading of complex characters, processing of their radicals occurs (e.g., Ding et al., 2004; Tsang & Chen, 2009; Zhou et al., 2013). Some of the studies providing such evidence have investigated whether the meanings of semantic and phonetic radicals are activated in reading phonetic compounds (e.g., Feldman & Siok, 1999; Zhou et al., 2013; Zhou & Marslen-Wilson, 1999). For example, using a primed lexical-decision task, Feldman and Siok (1999) found that target identification is facilitated when a prime character and a target character share a semantic radical that is related to the prime character's

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meaning, whereas target identification is delayed when their shared semantic radical is unrelated to the prime character's meaning. Similar priming results were obtained by Zhou et al. (2013). Zhou and Marslen-Wilson (1999) observed facilitatory priming effects for targets (e.g., 紫, /zi[3]/, "purple") that were semantically related to the phonetic radicals (e.g., 青, /qing[1]/, "blue") embedded in complex characters (e.g., 猜, /cai[1]/ "guess"), but not to the complex characters themselves, which implies that reading complex characters involves decomposing phonetic radicals and mapping them onto their own semantic representations, thus speeding up the responses to targets. Zhou and Marslen-Wilson (1999) also found an inhibitory priming effect when the semantic primes (e.g., 紫) were related to the phonetic radicals (i.e., 青) embedded in the complex character targets (e.g., 猜) but not to the targets themselves, implying that preactivation of phonetic radicals by primes strengthens the decomposition process and semantic access to radicals, slowing down the responses to targets.

Two models have been offered to explain the processing of radicals' meanings in reading complex characters. The connectionist model proposed by Zhou and colleagues (Zhou & Marslen-Wilson, 1999; Zhou, Shu, Bi, & Shi, 1999) emphasizes that the complex characters and their radicals are represented at the same level and activated in parallel; reading complex characters involves decomposing semantic or phonetic radicals and mapping them onto their semantic representations. Such decomposition may slow responses to the complex characters when their radicals' meanings are preactivated, leading to stronger competition between the meanings of the complex character and those of its radicals. According to the interactive activation model proposed by Taft and colleagues (Ding et al., 2004; Taft, 2006; Taft, Zhu, & Peng, 1999), for a visually presented word, when the character or its radicals are activated, their corresponding lemmas, and then the semantics and phonology of each lemma, can be activated. This model asserts that radicals' meaning can be processed, but it does not address whether such semantic processing would affect their host characters' processing.

Numerous studies with the Stroop color-identification task have examined this task's implications for reading and reading development, mainly through indirect measures of word recognition (e.g., Cho, Choi, & Proctor, 2012; Cho, Lien, & Proctor, 2006). Those studies with the Stroop task have shown that the color word affects performance even though it is irrelevant to the responses to the target's color. This Stroop effect indicates that the color word's meaning is processed involuntarily (e.g., Brown, Gore, & Carr, 2002; MacLeod & Dunbar, 1988), although the magnitude of this effect may be a function of the likelihood that the word captures visual attention (e.g., Cho et al., 2012; Waechter, Besner, & Stolz, 2011).

Ideogrammic compounds differ from the more widely studied phonetic compounds (e.g., Feldman & Siok, 1999; Zhou et al., 2013; Zhou & Marslen-Wilson, 1999), in that they are constructed by combining two or more radicals' meanings, rather than from a phonetic radical and a semantic radical. The radicals in an ideogrammic compound are unrelated to the host character in pronunciation, and few studies, to our knowledge, have considered whether the processing of radicals occurs during reading of ideogrammic compounds.

In the present study, therefore, we used a spatial variant of the Stroop task to investigate whether the radicals' meanings also are involved in reading ideogrammic compounds. This outcome could provide further converging evidence that in reading complex characters, their radicals can be decomposed and can access their own meanings, and it would test the implications of the above-reviewed connectionist and interactive activation models. In a location word version of the spatial Stroop task, the word *up* or *down* appears randomly above or below a fixation sign. Although participants are asked to identify the location of the word relative to the fixation cross while ignoring the word itself, or to identify the word while ignoring its location, participants typically make faster and more accurate responses to congruent stimuli (i.e., the word *up* above the fixation sign) than to incongruent ones (i.e., the word *down* above the fixation sign; see, e.g., Lu & Proctor, 1995; Luo & Proctor, 2013).

Experiment 1

We had participants identify two simple characters, 上 ("up") and 下 ("down"), as well as the complex characters 忐 ("nervous") and 忑 ("nervous") that contain a radical 上 or 下, which were presented above or below the central fixation cross. (For a list of all of the characters used in this study, please refer to Table 1.) The interactive model asserts that reading complex characters provides access to their radicals' meanings, so it predicts the emergence of Stroop effects for complex characters

Table 1 Chinese characters used in this study

	Simple Character		Complex Character	
Character	上	东	忐	陈
Frequency	63,200	2,853	0	342
Stroke number	3	5	7	7
Meaning	above	east	nervous	state
Pronunciation	/shang4/	/dong1/	/ tan3/	/chen1/
Character	下	西	忑	洒
Frequency	8,833	2,625	0	320
Stroke number	3	6	7	9
Meaning	below	west	nervous	spray
Pronunciation	/xia4/	/xi1/	/te4/	/sa3/

The numeral following each pronunciation refers to tone. Frequency counts are presented from the *Modern Chinese Frequency Dictionary* (Beijing Language Institute, 1985).

(忐 above or 忑 below the fixation vs. 忑 above or 忐 below fixation) as well as for simple characters. The connectionist model predicts a smaller Stroop effect for complex than for simple characters: When identifying the complex characters, their radicals 上 and 下 could be decomposed and access their own meanings that would be congruent or incongruent with the locations of the characters, which would increase, to different extents, the competition between the underlying representations corresponding to the radicals and the characters, and then slow down, to different extents, the responses to the characters, producing a Stroop effect. However, the competition and incomplete decomposition should result in a smaller Stroop effect than would be found for the simple location characters.

Method

Participants A group of 22 undergraduate students performed the task of identifying 上 and 下, and 22 different undergraduate students performed the task of identifying 忐 and 忑. All were native speakers of Chinese (Putonghua) and had normal or corrected-to-normal vision, and all were naive to the purpose of the experiments. All of the participants could recognize the four characters, partly because 忐忑 ("nervous") is the name of a popular song (in China) that is peculiar and has no lyrics.

Apparatus and stimuli The stimuli included four characters, 上, 下, 忐, and 忑, that were presented on a super VGA high-resolution color monitor with a black background. Each character was 2.5º × 2.5º of visual angle. Participants viewed the monitor from a distance of approximately 57 cm in a dimly lit room. A computer, running E-Prime 1.1 software, controlled the presentation of stimuli, timing operations, and data collection.

Procedure and design Each trial began with a central red fixation cross (0.4º × 0.4º). After 1 s, one character appeared 3.5º of visual angle above or below the fixation cross until the participant responded or until a 1,500-ms time limit elapsed. After that, the next trial began. The interval between trials was 1 s, and the screen remained black throughout this interval.

For each set of spatial Stroop stimuli (上 and 下) or (忐 and 忑), two trial blocks were presented with a rest of 30 s between them, and their order was randomized across participants. Each block started with 16 practice trials, followed by 64 test trials presented in a random order, with 32 for the congruent condition [上 above (16) and 下 below (16) the fixation cross, or 忐 above (16) and 忑 below (16) the fixation cross] and 32 for the incongruent condition [上 below (16) and 下 above (16) the fixation cross, or 忐 below (16) and 忑 above (16) the fixation cross]. Therefore, the experiment had a 2 (stimulus set: 上 and 下 vs. 忐 and 忑) × 2 (congruency: congruent vs. incongruent) design. Stimulus set was a between-subject variable, whereas the other variable was manipulated within subjects.

When identifying 上 and 下, the task was to press the "V" key for 上 and the "M" key for 下 on the bottom row of the computer's keyboard in one trial block, and to use the reverse mapping in the other trial block. The same pairings of characters and keys were true when identifying 忐 and 忑. The response keys and computer screen were aligned such that the fixation point and the midway point between the two response keys were on the participant's sagittal midline. Participants were instructed to maintain fixation and to respond to the targets as quickly and accurately as possible.

Results and discussion

Mean reaction times (RTs) and percentage errors (PEs) are shown in Table 2. An analysis of variance (ANOVA) on RTs showed a significant main effect of stimulus set, $F(1, 42) = 10.90$, $MSE = 24{,}012$, $p = .002$, $\eta_p^2 = .206$, with faster responses to simple (481 ms) than to complex (558 ms) characters. The main effect of congruency was also significant, $F(1, 42) = 30.36$, $MSE = 488$, $p < .001$, $\eta_p^2 = .420$, showing an 18-ms Stroop effect. The interaction of those variables was not reliable ($F < 1$), showing no significant difference in the sizes of the Stroop effect for the two stimulus sets.

Even though the interaction was not reliable, we performed an ANOVA for each stimulus set with congruency as a within-subjects variable in order to confirm that the Stroop effect was significant for each stimulus set when analyzed alone. These ANOVAs showed reliable Stroop effects of 20 ms for simple characters, $F(1, 21) = 17.10$, $MSE = 534$, $p < .001$, $\eta_p^2 = .449$, and 16 ms for complex characters, $F(1, 21) = 13.27$, $MSE = 443$, $p = .002$, $\eta_p^2 = .387$.

The ANOVA on PEs showed a main effect of stimulus set, $F(1, 42) = 6.42$, $MSE = .003$, $p = .015$, $\eta_p^2 = .133$, with more error responses made to complex characters (4.4 %) than to simple characters (2.2 %). The main effect of congruency and its interaction with stimulus set were not significant (Fs < 1).

In this experiment, responding was faster and more accurate to simple than to complex characters, which could have occurred because simple characters have both higher frequency and fewer strokes than complex characters. Another possibility is that processing of the radical inhibits identification of the complex character, as was observed by Zhou and Marslen-Wilson (1999), who found an inhibitory effect for complex-character targets preceded by primes semantically related to the phonetic radicals composing the targets, but not to the targets themselves.

As is predicted by the connectionist and interactive models, a Stroop effect was obtained for simple characters, indicating that location information of characters interfered with their identification; notably, a Stroop effect also occurred for complex characters, indicating that the location information of complex characters interfered with processing of their radicals. These results suggest that the meaning of radicals is processed.

Table 2 Reaction times (measured in milliseconds) and percentage errors (in parentheses) for each condition

	Experiment 1		Experiment 2		Experiment 3	
	SC	CC	SC	CC	SC	CC
Congruent	471 (2.1)	550 (4.2)	374 (1.5)	386 (1.2)	489 (1.9)	508 (2.3)
Incongruent	491 (2.3)	566 (4.6)	383 (1.5)	398 (1.1)	502 (2.6)	518 (6.4)

SC = simple characters, CC = complex characters

However, inconsistent with the prediction of the connectionist model, the Stroop effects were of similar size for simple and complex characters, indicating that the processing of the other radical and the complex character had little or no effect on the processing of the radicals 上 and 下.

However, it is also possible that these results arose purely from a task-specific strategy, because the radical 心 is the same in both 志 and 忑, which might make participants focus solely on the top half of the characters in order to perform the task. To exclude this possibility, we performed Experiment 2, in which the locations of the characters needed to be determined. As in Experiment 1, the connectionist and interactive models both predict a spatial Stroop effect, with the former also predicting an interaction with stimulus set.

Experiment 2

Method

Participants A group of 44 new participants was recruited from the same pool as in Experiment 1. Half of the participants performed the task of identifying 上 and 下, and the remaining performed the task of identifying 志 and 忑.

Apparatus, stimuli, procedure, and design These were identical to the same aspects of Experiment 1, except that the task was to indicate the location occupied by the character.

Results and discussion

Mean RTs and PEs are shown in Table 2. An ANOVA on RTs showed a main effect of congruency, $F(1, 42) = 14.47$, $MSE = 345$, $p < .001$, $\eta_p^2 = .256$, indicating an 11-ms overall Stroop effect. The main effect of stimulus set and the interaction were not significant (Fs < 1), showing no significant differences in the sizes of the spatial Stroop effect for the two stimulus sets. In line with the analysis of RTs in Experiment 1, an ANOVA for each stimulus set showed reliable Stroop effects of 12 ms for simple characters, $F(1, 21) = 16.42$, $MSE = 112$, $p = .001$, $\eta_p^2 = .439$, and 9 ms for complex characters, $F(1, 21) = 5.64$, $MSE = 579$, $p = .027$, $\eta_p^2 = .212$. The ANOVA on PEs showed no reliable main effects or interaction (Fs < 1).

As in Experiment 1, and as predicted by the connectionist and interactive models, Stroop effects emerged for both simple and complex characters. Because participants need not process the internal constituents of the character in this experiment, the Stroop effect for complex characters could not arise purely from a task-specific strategy. Inconsistent with the predictions of the connectionist model, the sizes of the spatial Stroop effect were similar for simple and complex characters, indicating that processing of the other radical and of the complex character had little or no effect on the processing of the radicals 上 and 下.

Experiment 3

In this experiment, we examined whether the findings observed in Experiment 1 would be generalizable to another set of stimuli: 陈 (“state”) and 洒 (“spray”), which contain 东 (“east”) and 西 (“west”) as radicals. The predictions of the connectionist and interactive models were the same as in Experiment 1.

Method

Participants A group of 44 new participants was recruited from the same pool as in Experiment 1. Half of the participants performed the task of identifying 东 and 西, and the remaining half performed the task of identifying 陈 and 洒.

Apparatus, stimuli, procedure, and design These were identical to the same aspects of Experiment 1, except that the two sets of Stroop stimuli were 陈 (“state”) and 洒 (“spray”), or 东 (“east”) and 西 (“west”), and that they were presented to the left or right of the fixation.

Results and discussion

Mean RTs and PEs are shown in Table 2. An ANOVA on RTs showed a significant main effect of congruency, $F(1, 42) = 18.02$, $MSE = 174$, $p < .001$, $\eta_p^2 = .300$, with a 12-ms Stroop effect. The main effect of stimulus set and the interaction with congruency were not significant (Fs < 1), showing no significant difference in the sizes of the Stroop effects for the two stimulus sets. In line with the analysis of RTs in Experiment 1, an ANOVA for each stimulus set showed a significant Stroop effect of 13 ms for simple characters, $F(1, 21) = 17.08$, $MSE =$

124, $p < .001$, $\eta_p^2 = .448$, and of 9 ms for complex characters, $F(1, 21) = 4.93$, $MSE = 224$, $p = .038$, $\eta_p^2 = .190$.

The ANOVA on PEs showed that the main effects of congruency and stimulus set, as well as their interaction, were all significant: $Fs(1, 42) = 16.21$, 6.92, and 8.67; MSEs = .001; ps < .001, .012, and .005; and η_p^2s = .278, .141, and .171, respectively. Further analyses showed a significant Stroop effect in PEs for complex characters (4.1 %), $F(1, 21) = 15.97$, $MSE = .001$, $p = .001$, $\eta_p^2 = .432$, but not for simple characters (0.7 %), $F(1, 21) = 1.22$, $MSE = .001$, $p = .282$, $\eta_p^2 = .055$.

Using another set of stimuli—陈 ("state") and 洒 ("spray"), which contain 东 ("east") and 西 ("west") as radicals—we replicated the main findings of Experiment 1, including that Stroop effects emerged for both simple and complex characters, as predicted by the connectionist and interactive models. Inconsistent with the prediction of the connectionist model, the Stroop effects were of similar sizes for the simple and complex characters. Thus, the findings in Experiment 1 are generalizable. In addition, as was not the case in Experiment 1, responding was not faster to simple than to complex characters, which could have occurred because the simple and complex characters for Experiment 3 were of high frequency.

General discussion

In this study, using a spatial Stroop task, we investigated whether, in reading ideogrammic compounds, the meanings of their radicals are also involved and used the results to examine the connectionist and interactive activation models. A spatial Stroop effect of similar size emerged when participants identified two simple characters, 上 and 下, or two ideogrammic compounds, 忐 and 忑, that appeared respectively above or below the central fixation cross in Experiment 1. In Experiment 2, we excluded the possibility that the findings in Experiment 1 arose purely from a task-specific strategy in which participants focused solely on the top half of the characters to perform this task, because both 忐 and 忑 have the radical 心. In Experiment 3, using another set of stimuli, 陈 and 洒, that contain 东 and 西 as radicals, we replicated the main findings of Experiment 1, showing them to be generalizable. These findings imply that in reading ideogrammic compounds, (1) their radicals are decomposed and can access their own meanings; and (2) ideogrammic compounds do not have much, if any, influence on the semantic processing of their radicals, suggesting the processing of an ideogrammic compound and of its radical in parallel.

The findings of processing of radicals' meanings in reading ideogrammic compounds are parallel to the findings of sublexical semantic processing of semantic radicals (e.g., Feldman & Siok, 1999) and phonetic radicals (e.g., Zhou & Marslen-Wilson, 1999, 2002) embedded in phonetic compounds. These results together provide converging evidence that semantic processing of radicals emerges in reading complex Chinese characters.

Taft's model (Ding et al., 2004; Taft, 2006; Taft et al., 1999) can explain the Stroop effect occurring in Experiments 1 to 3, because activation of the radicals' representations is mediated by their corresponding character representations, which link to their phonological and semantic information via lemma units.

The connectionist model proposed by Zhou and colleagues (Zhou & Marslen-Wilson, 1999; Zhou et al., 1999) can also explain the Stroop effect occurring in Experiments 1 to 3, given that reading complex characters involves decomposing radicals and accessing their own meanings. However, this model cannot explain the Stroop effects being of similar size in reading simple and complex characters. This is because the radicals 上 or 下 could be decomposed and access their own meanings, which are congruent or incongruent with the locations occupied by the complex characters, thereby increasing to different extents the competition between the underlying representations corresponding to radicals and to characters. In turn, this competition would slow down, to different extents, the responses to the characters, creating a Stroop effect, but one that is smaller due to the competition and to incomplete decomposition.

During reading of ideogrammic compounds, their radicals' meanings can be activated because of the structure of these characters and the learning processes in acquiring them. Structurally, radicals usually have a clear visual separation that provides cues for the visual decomposition of radicals in lexical access. Functionally, ideogrammic compounds are more similar to compound words than to mono-morphemic words, since they have functionally salient components. Therefore, radicals' processing is similar to morphemic processing in reading Chinese compound words. Furthermore, the relations between radicals and the ideogrammic compounds are either explicitly or implicitly taught to children when they learn characters. These properties make radicals very salient orthographic and functional units in complex characters. It thus becomes not only natural, but also compulsory, to decompose such units from visual input and to activate their semantic properties in the lexicon.

In conclusion, using a spatial Stroop task, in this study we found spatial Stroop effects of similar size for simple characters and ideogrammic compounds. We argue that, in reading Chinese ideogrammic compounds, their radicals can be decomposed and map onto their own semantic representations, in parallel to the processing of whole characters.

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