Psychonomic Bulletin & Review (2021) 28:610–623
https://doi.org/10.3758/s13423-020-01828-2

BRIEF REPORT

Functional orthographic units in Chinese character reading: Are there abstract radical identities?

Shi Pui Donald Li [1] · Sam-Po Law [2] · Kai-Yan Dustin Lau [3] · Brenda Rapp [1]

Accepted: 12 October 2020 / Published online: 6 November 2020

Abstract
Previous research has shown that the components of Chinese characters (e.g., semantic components, phonetic components, and radicals) serve as processing units in reading. One outstanding question concerns the existence of amodal orthographic representations that unify multiple, form-specific character components, similar to the abstract letter identities (ALIs) that unify case-specific letter forms (A/a) in Roman script. Although Chinese does not have case, a subset of semantic radicals have multiple forms (e.g., 氵–水 are both "water" radicals), allowing for a test of the existence of Abstract Radical Identities (ARIs) that unify the multiple forms. In Experiment 1, a visual same–different judgement task was used to detect the presence of ARI representations. Evidence for ARIs was provided by the finding that radical pairs with different forms but the same radical identity were judged to be visually different more slowly than matched pairs of different forms with different radical identities. In Experiment 2, we evaluated ARI effects in real character reading. A lexical decision priming task compared prime–target character pairs containing radicals with the same identity but different forms (e.g., 泄–泉) with matched prime–target character pairs with unrelated radicals (e.g., 無–泉). Inhibitory priming was observed only in the same-identity radical condition compared with the unrelated condition. These combined results provide, for the first time, evidence of format-free representations of orthographic units in Chinese characters—abstract radical identities (ARIs).

Keywords Orthography · Reading · Visual word recognition · Psycholinguistics

In the Roman alphabet, each letter can be represented in multiple modalities and formats, including visual-spatial representations that differ in font and case, motoric representations and phonological letter-name representations (see Fig. 1). In addition, abstract letter identities (ALIs) have been posited. These are amodal and abstract symbolic representations that do not contain any visual, phonological, or motor information (Rothlein & Rapp, 2014). ALIs serve as an interface between the modality-specific representations of letters used in different tasks, including reading and spelling. While the ALI representation is found in many scripts, including Roman letters and Arabic (Carreiras, Perea, & Mallouh, 2012), one unanswered question is whether abstract symbolic representations of orthographic elements exist even in nonalphabetic scripts such as Chinese.

Chinese is a logographic script that is composed of characters what correspond to a single syllable and, in most cases, also to a single morpheme. A character appears in a standard square space and typically consists of more than one orthographic component, one of which is called a radical (部首). The term "radical" is sometimes used in a general sense to refer to components in Chinese characters. However, we will use it to refer the specific orthographic component within a character that serves as a "classifier" to organize characters into different sections in a Chinese dictionary. Out of a total of 560 orthographic components ("Chinese Character Component Standard," 1997), only a subset of components are radicals—for example, there are 214 radicals in the Kangxi dictionary (Fang & Wu, 1989), and each character has only one radical. In most characters, the radical is also the semantic component of the character. Over time, some radicals developed different forms to increase flexibility for fitting into characters with different spatial layouts. For instance, 氵 and 水 are both "water" radicals, and

✉ Shi Pui Donald Li
sli97@jhu.edu

1 Department of Cognitive Science, The Johns Hopkins University, 237 Krieger Hall, 3400 N Charles Street, Baltimore, MD 21218, USA

2 Division of Speech and Hearing Sciences, University of Hong Kong, Pok Fu Lam, Hong Kong

3 Department of Chinese and Bilingual Studies, The Hong Kong Polytechnic University, Hung Hom, Hong Kong

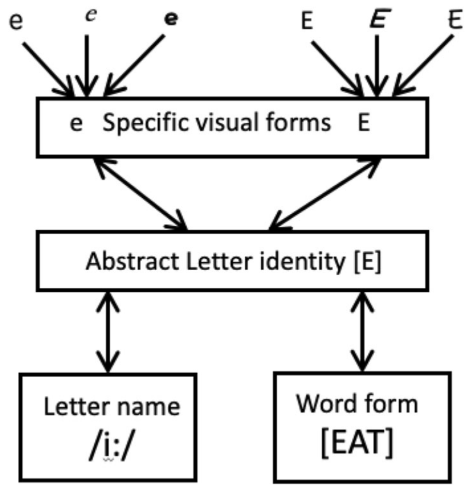

Fig. 1 The multiple formats of letter representation and their relationships to ALIs (abstract letter identities), Adapted from Rothlein and Rapp (2014).

although they have the same radical identity and index the same section in a traditional Chinese dictionary, the two forms are visually very different. This characteristic of Chinese orthography raises the question of whether different forms of the same radical identity share an abstract representation, what we will refer to as the abstract radical identity (ARI). ARIs would be analogous to ALIs in that both radical forms have the same high-level abstract radical identity despite having different low-level visual feature representations.

In this investigation, we carried out two experiments to test the hypothesis that ARIs exist and play a role in Chinese character reading. According to the ARI hypothesis (see Fig. 2), each ARI is associated with its different orthographic forms, and a single semantic meaning (although the characters in which they are embedded will have different meanings). In Experiment 1, we used a same–different judgement task to determine whether pairs of radicals that share radical identities but have different forms would be judged to be visually different more slowly than different radical pairs that do not share a radical identity. In Experiment 2, we used a lexical decision priming task, presenting radicals within characters, to examine if ARIs are accessed in character reading. We compared trials in which prime and target characters shared the same radical identity (but different forms) to various trial types in which the prime and target characters did not share radical identities. The ARI hypothesis predicts that when prime and target characters share the same radical identity, the preactivation of the radical identity in the target character by the prime will influence subsequent processing of the target character.

Experiment 1

In a same–different judgement task, the existence of ARIs would be supported if stimulus pairs with the same radical identity/different forms exhibit slower discrimination times than stimulus pairs with different radical identity/different forms. The logic is that although both types of radical pairs should yield "different" responses, it should take longer to make a "different" judgment for pairs sharing an ARI due to the time required to resolve the conflicting information regarding visual dissimilarity in the context of ARI identity. However, given that visual or semantic similarity may influence same–different responses, these variables must be taken into account. We did so analytically, using linear mixed-effect modelling to regress out the effects of visual, orthographic, and semantic confounds, allowing us to determine whether there is an effect of radical identity after factoring out the confounds. A similar approach has been used in Chinese (Zhai & Fischer-Baum, 2019) as well as in Roman and Arabic scripts (Wiley, Wilson, & Rapp, 2016).

Methods

Participants There were 36 right-handed, healthy participants between the ages of 18 and 65 years (one left-handed) with normal or corrected-to-normal vision, native Chinese speakers (28 Cantonese, eight Mandarin), originating from Hong Kong or Taiwan. They had secondary education and reported they were fluent and frequent readers of traditional Chinese. Written consent was obtained, and reimbursement was $10. The study was approved by the Johns Hopkins Homewood Institutional Review Board and the Human Research Ethics Committee of the University of Hong Kong.

Materials and design Seventeen different radical identities (14 with two radical forms and three with one) with a total of 31 different radical forms were combined to create a pool of 465 radical pairs. Using Amazon's Mechanical Turk, visual and semantic similarity ratings were collected for this item pool. Fifty non-Chinese speakers judged their visual similarity and 37 Chinese speakers judged their semantic similarity using a scale ranging from 1 to 5 (1 = low *similarity*; 5 = *high similarity*). None of the raters participated in the subsequent experiment. From this pool, 98 pairs with a total of 30 different radical forms (14 with two radical forms and two with one) were selected to constitute the three experimental conditions (see Table 1). The two radicals with only one form were used for their visual similarity to other radical forms (e.g., 力–刀 and 大–犬) to allow for a wide range of visual similarities. Each radical form was presented with roughly similar frequency throughout the experiment, ranging from 32 to 48 times:

1. Same radical/same form (SR/SF): 28 pairs of identical radicals. Each was repeated 10 times, for a total of 280 "same" response trials.
2. Same radical/different form (SR/DF): 14 pairs of radicals sharing the same identity and semantic meaning, but with

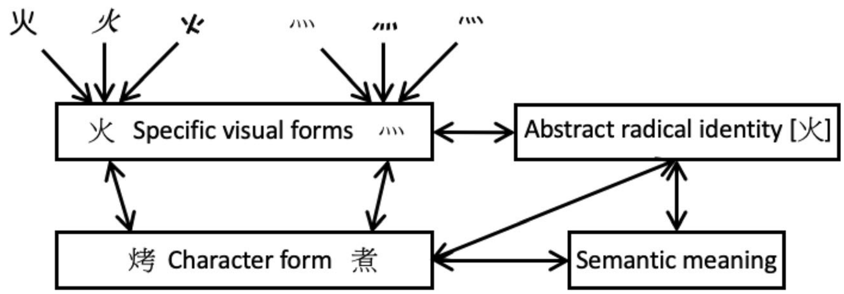

Fig. 2 Abstract radical representations included within a character processing system used in reading

different forms. Each was repeated four times, for a total of 56 trials.

3. Different radical/different form (DR/DF): 56 pairs of radicals with different forms, semantic meaning, and radical identities. (Note that the two radicals that have only one form were included in 10 radical pairs out of the total set of DR/DF pairs.) There were more radical pairs in this condition to ensure a better estimation of visual and semantic similarity by sampling a broader pool of radical pairs. Each pair was repeated four times such that, in combination with Condition 2, there was a total of 280 "different" response trials in the experiment.

Radical pairs were displayed diagonally rather than horizontally to prevent them from being misperceived as complex characters (e.g., '木' (left) and '目' (right) could be misperceived as the character '相'). Across the experiment, pairs were displayed in all four diagonal arrangements.

Experiment 1 consisted of 560 randomized trials divided into four blocks of 140 trials. Half of the trials (280 trials) consisted of identical radicals (eliciting a "same" response), while the other half consisted of two different radicals (eliciting a "different" response).

Procedure Participants were seated in front of an LCD monitor and asked to judge, as quickly and accurately as possible, whether the two character components that appeared on each trial were visually the same or different by pressing one of two buttons. Before the main experiment there were 10 practice trials, using a different set of radicals from the main experiment. Stimuli were presented using Psychtoolbox, MATLAB R2015B (Kleiner, Brainard, & Pelli, 2007). After each block, participants were informed if their accuracy was above 85% and, if it was not, they were encouraged to improve. Within each trial, a fixation cross was displayed for 250 ms, followed by a pair of radicals that remained on the screen until a response was made or until 2,500 ms had elapsed. After each trial, a 1,000 ms blank screen appeared before the next trial (see Fig. 3).

After the main experiment, participants carried out a radical knowledge assessment by choosing from among four radicals, the radical identity corresponding to each visually presented character (e.g., they were asked to choose 水 "water radical identity" for the character 淺). This test included 30 compound characters from the main experiment. An analogous task for the Roman alphabet would be to identify the uppercase letter corresponding to the first letter of a word (e.g., for **a**pple: V, A, S, or D).

Data analysis One subject was removed from further analysis for scoring below 80% on the radical knowledge test. For all participants, responses greater than three standard deviations from the mean of that participant's reaction times for each condition were discarded (~3% of trials), and only correct "different" response trials were included in the analysis.

Linear mixed-effect modelling was used to model reaction time, with normalized log-transformed reaction times (to address positive skew) as the dependent variable. Generalized linear mixed-effect modelling (GLM) was used to model accuracy with a logit link function. Both accuracy and RT models included the following as fixed effects: experimental conditions (with DR/DF serving as the baseline); semantic similarity and visual similarity based on Mechanical Turk

Table 1 The three experimental conditions in Experiment 1

Condition	Identity shared	Example Radical 1	Example Radical 2	Correct response	Mean visual similarity (range)	Mean semantic similarity (range)
Same radical/Same form (SR/SF)	Yes	水 [Water]	水 [Water]	Same	5 (5–5)	5 (5–5)
Same radical/Different form (SR/DF)	Yes	氵 [Water]	水 [Water]	Different	2.58 (1.5–4)	5 (5–5)
Different radical/Different form (DR/DF)	No	忄 [Heart]	竹 [Bamboo]	Different	2.24 (2–4.5)	2.55 (2–3.25)

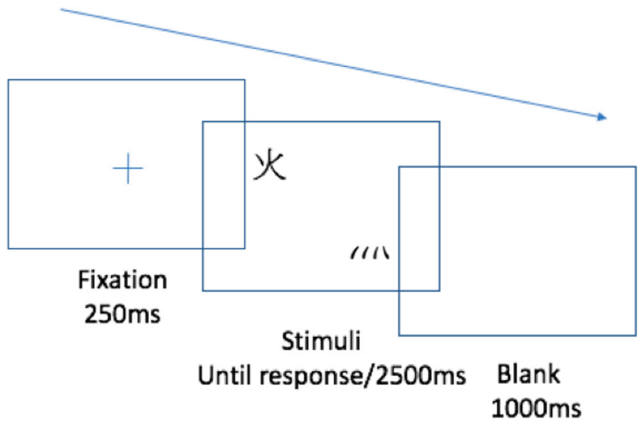

Fig. 3 Sample trial in the same–different paradigm

rating; difference in number of strokes between the two radical forms (stroke difference); screen position of radicals (presentation position: a categorical variable that codes whether the pairs appear in the upper left/lower right or upper right/lower left) and functional role difference of the two forms (i.e., a categorical variable that coded if both forms were either two pure radicals or if both forms could be standalone characters, they were considered to be functionally "same"; otherwise, they were "different"). Both models included the random slope of experimental condition and random intercepts by subjects and blocks to regress out individual differences. Since there was a concern that the lack of variance in the semantic similarity of the DR/DF condition would cause a collinearity between the experimental condition and the semantic similarity condition, a variance inflation factor (VIF) was calculated for each fixed effect to evaluate the severity of multicollinearity. The "lme4" and "lmerTest" library in R was used for the analysis, and *p* values were computed using the *t*-as-*z* method (Luke, 2017).

Results

Table 2 reports mean condition-specific accuracies and reaction times; Tables 3 and 4 reports the reaction time linear mixed-effect modelling (LMEM) and accuracy GLM results. The results show significantly longer reaction times ($p < .001$) and marginally lower accuracy ($p < .07$) for the SR/DF than the DR/DF condition when controlling all other confounds.[1] In addition, visual similarity (RT: $p < .001$; accuracy: $p < .001$), number of strokes difference (RT: $p < .001$; accuracy: $p < .05$), and semantic similarity (RT: $p < .001$; accuracy: $p < .08$) had significant/marginally significant effects on reaction time and accuracy, while functional role difference (RT: $p > .10$; accuracy: $p > .10$) and presentation position (RT: $p > .10$; accuracy: $p > .10$) had no significant effects in either reaction time and accuracy. In both analyses, VIF values for all variables were under 10, indicating an acceptable degree of correlation between variables (Hair, Anderson, Tatham, & Black, 1995).

Table 2 Experiment 1: Mean reaction times, accuracies, and visual and semantic similarity ratings

Condition	Sample pair	Mean reaction time in ms (*SD*)	Accuracy (*SD*)
Same radical/Same form	水–水	636.98 (175)	98% (16%)
Same radical/Different form	氵–水	705.73 (217)	94% (23%)
Different radical/Different form	忄–竹	636.22 (162)	97% (16%)

Summary

The SR/DF pairs exhibited slower reaction times and lower accuracy, even after considering the effects of visual and semantic similarity, visual complexity differences, and functional differences. It is important to note that Chinese readers judged radicals differently from naïve readers, as evidenced by the fact that Experiment 1 results could not be solely explained by visual similarity (naïve readers' judgement), but other variables like semantic similarity and ARI information were needed. These findings indicate that when making a same–different judgement for the visually different SF/DF trials, it is difficult to suppress the information that both radicals have the same identity and, thus the findings are clearly consistent with the ARI hypothesis. Experiment 2 was conducted to address the ARI hypothesis using a more "naturalistic" presentation of radicals within characters. This would address a possible concern regarding Experiment 1, that because some radicals are not stand-alone characters, readers may not have previously encountered them in isolated form in their daily reading. In addition, Experiment 2 was designed to explicitly address the possible confound between ARI and semantic meaning—namely, that radicals with the same ARI also have the same meaning.

Experiment 2

We used a lexical decision priming experiment in which—on every trial—the prime was always a Chinese character and the target was either a real Chinese character or a pseudocharacter. According to the ARI hypothesis, we should observe different priming effects when prime and target share the same radicals/different forms (SR/DF) compared with when prime and target have different radicals/different forms (DR/DF). However,

[1] The exact same pattern was found when the 10 pairs of radicals in the DR/DF condition that contains radicals with only one form were removed. When comparing the SR/DF with DR/DF using the same LMEM method as in the Experiment 1 for the subset of stimuli, SR/DF shows a longer reaction time than the DR/DF condition ($p < .05$), supporting the ARI effect.

Table 3 Experiment 1: Results of LMEM reaction time analysis and variance inflation factor (VIF)

	Estimate	*SE*	*t* value	95% confidence interval	VIF
(Intercept)	6.4	0.04	158.5*	[6.3 6.5]	
SR/DF vs. DR/DF	0.08	0.02	3.5*	[0.04, 0.13]	6.3
Semantic similarity	0.07	0.01	5.3*	[0.04, 0.09]	6.2
Visual similarity	0.04	0.003	13.8*	[0.03, 0.04]	1.1
Number of strokes diff.	−0.02	0.003	−7.4*	[−0.03, −0.02]	1.2
Functional diff.	−0.003	0.006	−0.5	[−0.02, 0.01]	1.1
Screen position	0.006	0.005	1.1	[0.00, 0.02]	1

$^{*}p < .05$

because meaningful characters are involved, the semantic relationships between radicals and characters also has to be considered. Furthermore, since radicals with the same identity but different forms always have the same semantic meaning, it is important to establish that any priming effects in the SR/DF condition result from shared ARIs rather than semantic priming.

To this end, several measures were taken: (1) To avoid character–character semantic priming, prime and target characters were selected to be generally semantically unrelated and prime–target character semantic relatedness was matched across conditions, $F(2, 32) = 0.005$, $p = .99$. (2) We included a DR/DF condition with relatively strong semantic relatedness between prime and target radicals to allow evaluation of semantically based priming between form-different prime and target radicals. (3) To ensure that we were specifically evaluating semantic priming between prime and target radicals, prime and target characters were selected to have relatively low transparency (low semantic relatedness between a radical and the character in which it occurs). This helps ensure that semantic priming is not due to semantic similarity between prime characters and target radicals. Accordingly, we include both prime and target character transparency as an analysis covariate. (4) To further distinguish semantic from orthographic priming, we used two stimulus-onset asynchronies (SOAs; 55 and 200 ms). While orthographic priming is found at both short and long SOAs, semantic character-based priming was more likely to be observed only in longer SOAs (Liu, Perfetti, & Hart, 2003; Perfetti & Tan, 1998; Perfetti & Zhang, 1995).

Methods

Participants There were 36 right-handed participants, between 18 and 65 years of age, recruited from the University of Hong Kong, with normal or corrected-to-normal vision. They had all completed secondary education and self-reported fluency in reading traditional Chinese. Written consent was obtained, and reimbursement of HKD$75 was given. This study was approved by the Johns Hopkins Homewood Institutional Review Board and the Human Research Ethics Committee in the University of Hong Kong.

Materials and design There were three word conditions and one pseudocharacter condition. The pseudocharacters were constructed by combining components of real characters in their legal positions (Ding, Peng, & Taft, 2004; see Fig. 4). There was a total of 75 prime/character pairs and 75 prime/pseudocharacter pairs. Semantic transparency ratings of prime and target characters were obtained from the Hong Kong Newspaper corpus database (Leung & Lau, 2010). Semantic relatedness scores for prime–target pairs were obtained from the Chinese Latent Semantic Analysis Database (http://www.lsa.url.tw/modules/lsa/lsa_pairwise_comparison.php). Number of strokes were obtained from a Chinese dictionary (https://www.mdbg.net/chinese/dictionary?page=about). The experimental prime–target conditions were as follows:

1. **Same radical/different form (SD/DF):** Prime and target character pairs shared radical identities that have different forms. For example, prime character例 (meaning: example) and target character傘 (meaning: umbrella) have different radical forms亻 (the left component) and人 (the top component), but both of them have the same ARI of 人 (meaning: human).
2. **Different radical/different form, semantically related (DR/DF^{+SEM}):** Prime and target characters did not share a radical identity, but their radicals were semantically related (upper 50% in Experiment 1 semantic similarity ratings). For example, the prime character 今 (meaning: today) has the radical 人 (meaning: human; the top component) and the target character快 (meaning: fast) has the radical忄 (meaning: heart; the left component); in this case, the radical forms and ARIs are different, but are semantically related.
3. **Different radical /different form, semantically unrelated (DR/DF^{-SEM}):** Prime and target characters did not share a radical identity and their radicals were selected

Table 4 Experiment 1: Results of GLM accuracy analysis and variance inflation factor

	Estimate	*SE*	*t* value	VIF
(Intercept)	4.4	0.4	12***	
SR/DF vs. DR/DF	−1.2	0.6	−1.9**	8.4
Semantic similarity	−0.6	0.3	−1.8**	8.4
Visual similarity	−0.5	0.1	−7.5***	1.2
Number of strokes diff.	0.2	0.1	2.2*	1.2
Functional diff.	−0.1	0.2	−0.4	1.2
Screen position	0.1	0.1	0.7	1

$^{*}p < .05$, $^{**}p < .10$, $^{***}p < .001$

to be semantically unrelated (lower 50% in Experiment 1 semantic similarity ratings). For example, the prime character 何 (meaning: why) and the target character根 (meaning: root) have different radical forms and their ARIs are 亻 (meaning: human; left component) and 木 (meaning: wood; left component); in this case, the two ARIs are semantically unrelated.

Each of the experimental conditions consisted of 25 prime–target character pairs. Conditions were matched in terms of stroke number, $F(2, 72) = 0.112$, $p = .89$, prime character frequency, $F(2, 72) = 1.77$, $p = .18$, target character frequency, $F(2, 72) = 0.037$, $p = .96$, semantic similarity between prime and target characters, $F(2, 32) = 0.005$, $p = .99$, and spatial layout difference between prime and target character ($\chi^2 = 2.5$, $p = .40$; for details, see Table 5). The situation with regard to the semantic transparency of prime and target stimuli was more complex, as transparency ratings were available for only 70% of all character stimuli and 62% of experimental pairs. However, for those characters for which transparency ratings were available, the experimental conditions were comparable in terms of the semantic transparency of prime characters, $F(2, 32) = 0.9$, $p = .40$, and target characters, $F(2, 32) = 0.45$, $p = .65$.

There were a total 300 trials (150 character and 150 pseudocharacter targets), with presentation blocked by SOA (55 and 200 ms). Each prime–target pair was presented twice, once for each SOA condition. Blocks were counterbalanced across participants.

Fig. 4 Examples of pseudocharacters

Procedure Participants were seated in front of an LCD screen, and stimuli were presented using Psychtoolbox, MATLAB R2015B. Trial events (see Fig. 5) were as follows: fixation (200 ms), prime (either 55 ms or 200 ms), target presentation and lexical decision judgement (maximum 2,500 ms), blank screen (1,000 ms). Participants were instructed to judge the lexicality of the target character as quickly and accurately as possible by pressing different keys. Ten practice trials were included, and the Experiment 1 radical knowledge test was administered.

Data analysis Linear mixed-effects modelling and generalized linear mixed model analysis were used to examine the log-transformed reaction times and accuracy in the same way as in Experiment 1. Responses greater than three standard deviations from the mean of a participant's reaction times for that condition were discarded (~3% of trials). Trials with incorrect responses were not analyzed in the reaction time model. In both models, fixed effects were experimental condition (DR/DF^{-SEM} served as the baseline), number of prime strokes, number of target strokes, percentage of strokes shared by prime and target, percentage of pixel overlap between prime and target, previous trial accuracy, spatial layout difference between prime and target,[2] prime character frequency, target character frequency, "semantic" radical frequency (Leung & Lau, 2010) and semantic similarity between prime and target character. The random factor was the random intercept by participant. Separate models were evaluated for the 55 ms and the 200 ms SOA. VIFs are calculated for each fixed factor.

Results

Nine participants were removed from further analysis due to low accuracy (<60% accuracy of the lexical decision task). All remaining participants scored above 80% on the radical knowledge test. Table 6 and Fig. 6 report RT and accuracy results.

VIFs from all variables in all models were below 10, suggesting very little multicollinearity between variables. Reaction time analysis of the 55 ms SOA condition revealed the following: (1) Lexical decision times in the SR/DF condition were significantly slower than those in both DR/DF^{-SEM} ($z = 4$, $p < .0001$) and DR/DF^{+SEM} ($z = 3.3$, $p < .01$) conditions. (2) Lexical decision times in the DR/DF^{+SEM} condition were not significantly different from those in the DR/DF^{-SEM} condition ($z = 1.4$, $p = 0.35$). (3) There were significant effects

[2] Specifying whether the prime and target characters has the same spatial layout—that is, if the prime had a left/right layout (e.g., 餓 which has a left食 and right 我 component) and the target had a top/down layout (e.g., 裂 which has a top 列 and down 衣 component), then it is different.

Table 5 Experiment 2: Stimulus condition characteristics

Condition	Example prime–target (character meaning) [Radical: radical meaning]	Number of strokes in target (*SD*)	Target character frequency (*SD*)	Prime–target semantic similarity	Prime character transparency (*SD*)	Target character transparency (*SD*)
1. SR/DF	例 (example)– (umbrella) [亻: human] [人: human]	9.92 (4.41)	351 (407)	0.21 (0.14)	3.44 (0.14)	5.23 (1.52)
2. DR/DF^{+SEM}	今 (today)– (fast) [人: human] [忄: heart]	9.56 (3.01)	329 (645)	0.23 (0.14)	3.64 (0.29)	4.97 (1.2)
3. DR/DF^{-SEM}	何(why)– (root) [亻: human] [木: wood]	10 (2.86)	301 (820)	0.24 (0.19)	3.84 (0.38)	5.3 (1.3)

of target character frequency ($p < .01$), pixel overlap between prime and target characters ($p < .05$), spatial layout difference between prime and target ($p < .01$) and number of target character strokes ($p < .01$). See Table 7 in the Appendices for details. Reaction time analysis of the 200 ms SOA condition revealed significant differences between SR/DF and DR/DF^{-SEM} conditions ($z = 3.2$, $p < .01$), while SR/DF was marginally different from DR/DF^{+SEM} ($z = 1.9$, $p = .11$). There was no significant difference between the DR/DF^{+SEM} and DR/DF^{-SEM} condition ($z = 1.5$, $p = .30$). See Table 8 in the Appendices for details.

Accuracy models revealed no significant difference between conditions for either 55-ms or 200-ms SOAs, but there was a marginally significant difference between the SR/DF condition with the DR/DF^{-SEM} in the 55-ms SOA condition ($t = 2.1$, $p = .08$) such that there were more errors for SR/DF than for the DR/DF^{-SEM} condition. See Tables 9 and 10 in the Appendices for details.

Because, as indicated earlier, semantic transparency ratings were not available for 30% of characters, the same analyses were repeated using only the character pairs for which these ratings were available. The significant results were the same as those reported for the full set of items.

Summary

The results of Experiment 2 revealed a significant inhibitory priming effect such that lexical decision times were longer for target characters primed by characters that shared the same radical identity but in a different form (SR/DF) compared with targets primed by characters that did not share the same radical. Further, there was no evidence of semantic priming (excitatory or inhibitory) between prime and target radicals that did not share the same radical (DR/DF^{+SEM} vs. DR/DF^{-SEM}) supporting the conclusion that the radical priming that was observed was not due to semantic similarity between prime and target radicals. In combination, the findings provide strong evidence of abstract radical identity (ARI) representations.

General discussion

The results of two experiments provide evidence that the radical components of Chinese characters are likely to have abstract representations (abstract radical identities [ARIs]) that are independent of their spatial/geometrical and semantic

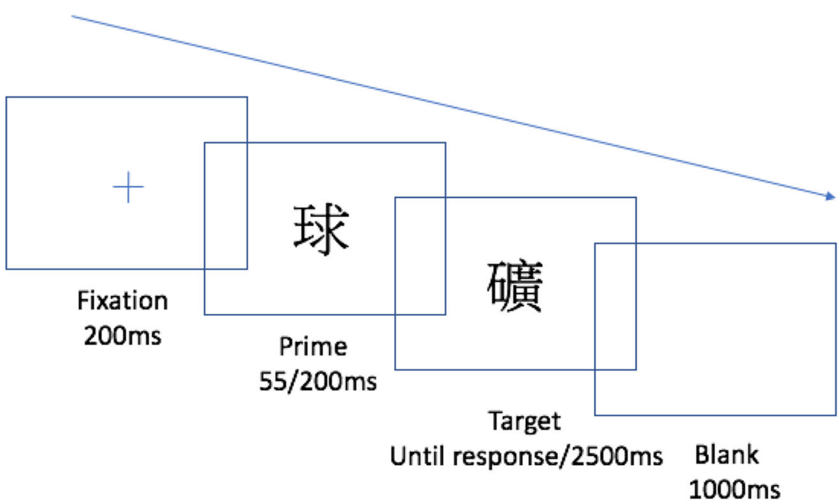

Fig. 5 Experiment 2 priming paradigm

Table 6 Experiment 2: Mean reaction times and accuracies, by SOA

Condition	Mean reaction time in ms (*SD*)	Accuracy
1. Same radical/different form (SR/DF)		
55-ms SOA	616 (192)	0.95 (0.21)
200-ms SOA	614 (180)	0.97 (0.18)
2. Different radical/different form, semantically related (DR/DF^{+SEM})		
55-ms SOA	599 (179)	0.97 (0.17)
200-ms SOA	608 (180)	0.98 (0.14)
3. Different radical/different form, semantically unrelated (DR/DF^{-SEM})		
55-ms SOA	595 (155)	0.99 (0.1)
200-ms SOA	605 (205)	0.99 (0.1)

features. The experiments specifically examined whether radicals that share the same identity but differ in form (e.g., 氵 –水) share a common ARI, which would be analogous to the abstract letter identities posited to unify cross-case forms (A/a) in alphabetic scripts (Besner, Coltheart, & Davelaar, 1984). One of the challenges in testing the ARI hypothesis is in distinguishing ARI from semantic effects, given that radicals with the same identity share the same semantic meaning. Furthermore, given recent findings supporting a role for visual similarity in same–different judgements (Zhai & Fischer-Baum, 2019), it is also critical to consider possible visual confounds. In the work we report on here, we found that in a same–different visual discrimination task (Experiment 1), even when analytically accounting for semantic and visual similarity, there was strong support for the existence of ARIs, based on both the reaction time and accuracy data. The conclusion was further strengthened by the Experiment 2 finding of inhibitory priming between same-identity/different-form radicals but not between different-identity/different-form radicals that were semantically related. Both of these findings constitute evidence that abstract radical representations cannot be reduced to semantic (or visual)

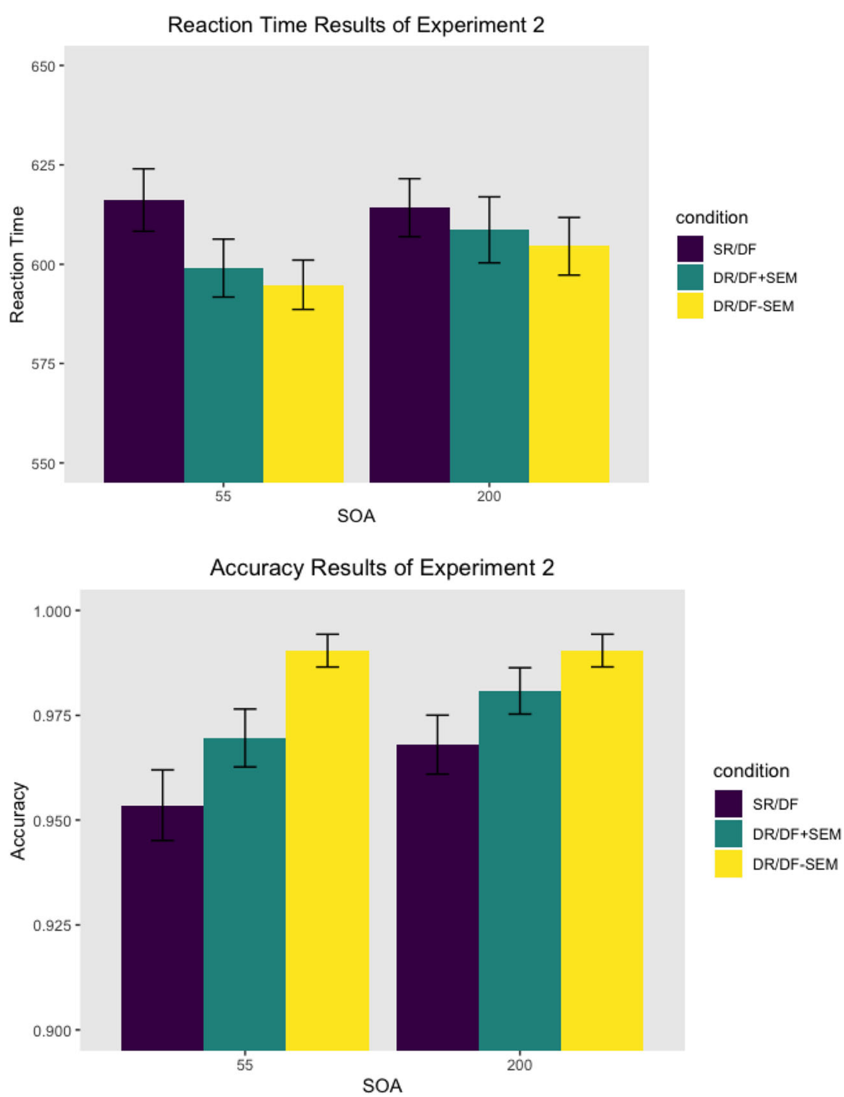

Fig. 6 Lexical priming effect according to prime condition and SOA, mean raw reaction time from correct trials (top), and accuracy (bottom)

representations, but, instead, correspond to symbolic representations of radical identity.

Character recognition in Chinese

Both Experiments 1 and 2 clearly reveal that there is a special representational/processing relationship between the different radical forms that correspond to the same radical identity. Given that the findings from Experiments 1 and 2 that these effects are not easily accounted for by either visual or semantic similarity, to explain the effects we introduced the notion of ARI representation. We incorporate this proposal into the model of Chinese character recognition proposed by Ding et al. (2004). As depicted in Fig. 7, the Ding et al. model assumes that complex character recognition involves the representation of position-specific radicals and complex characters at different levels with inhibitory links within each layer. We expand upon this framework by proposing that these different layers are mediated by ARIs.

Within this architecture, when a complex character is processed, it first activates form-specific and position-specific radical units which, in turn, activate their corresponding ARIs. For characters containing radicals that have multiple forms, the other (nonpresented) form-specific radical is dynamically inhibited. The form-specific and position-specific radical representations and the ARIs both go on to activate character representations, and, finally, both ARIs and character representations activate meaning representations. This framework allows for interpretation of a number of findings.

Position representation and ARIs Recent behavioral (Ding et al., 2004) and event-related potential (ERP) findings support the notion of position-specific character components. Components differ in terms of their position within characters. For instance, 氵 always appears on the left side of a character 河, 溜 (unique position), but never on the right (illegal position); whereas 子 appears on the left孩, the right 仔, and the bottom孕, but not at the top. Accordingly, there has been interest in understanding whether there are position-specific and/or position-general radical representations. Su, Mak, Cheung, and Law (2012) reported evidence of early ERP component sensitivity to position and Yum, Su, and Law (2015) showed sensitivity to violation of orthographic position within 150 ms from stimulus onset. These findings indicate position-specific radical representations in early stages of character processing. In the proposed architecture, position-specific components are plausibly form-specific representations (e.g., 子–left, 子–right, 子–bottom) that are then subsequently linked to ARIs which are, presumably, position general (e.g., 子).

Facilitatory and inhibitory semantic effects For transparent characters, since the meaning of the ARI is related to the meaning of the character, semantic processing is facilitated. In contrast, semantically opaque characters take longer to recognize because the semantic meaning of the ARI is not related to the meaning of the character, which does not, therefore, benefit from the semantic activation of the ARI and may create conflict, which takes time to resolve.

Feldman and Siok (1999) reported inhibitory lexical decision priming when target characters were primed by semantically opaque characters that shared the same target radical form, compared with unrelated primes. They situated this inhibitory radical priming effect at the semantic level, arguing that it takes longer to recognize the target character after the semantics of the shared radical is inhibited by the semantics of the prime character because the prime character and its radical do not share meanings.

Inhibitory effects of ARIs Critically, we have proposed that the inhibitory priming reported in Experiment 2 is not semantically based. Our rationale is as follows: First, previous work has found that the short SOAs at which we observed the inhibitory ARI effects allow for orthographic rather than a semantic priming (Tan & Peng, 1991); second, we observed minimal semantically based radical priming under the same experimental conditions in which strong inhibitory ARI effects were observed. Thus, to account for the observed inhibitory effects that we found, we assume that there is inhibition between the representations of the two forms of the same radical identity during character recognition. Accordingly, when a prime character is presented, one radical form is activated, and the other form is inhibited. As a result, when in a character containing the other member of the ARI is subsequently presented, lexical decision times are slowed. This stands in contrast to conditions where prime and target radicals are semantically related. Since they do not correspond to the same radical identity, there is no inhibition between them, and facilitatory semantic priming is expected (see Zhou, Peng, Zheng, Su, & Wang, 2013, for findings consistent with that expectation).[3]

Commonalities across different scripts

Interestingly, it is worth noting general representational similarities across scripts. For example, it has been proposed that Arabic script also has both position-specific and abstract position-independent orthographic representations. Despite clear differences across these scripts, the similarities between these findings, along with the ones reported in this paper, suggest that, among other key things, position-general abstract orthographic representations may be universal across languages (Carreiras et al., 2012; Wiley et al., 2016).

[3] Note: In Experiment 2, we do not observe semantic priming (DR/DF^{+SEM} compared with DR/DF^{-SEM}) presumably because the target characters are semantically opaque (character and radical have little semantic overlap) and thus do not benefit from the activation of the semantic representations of prime (or target) radicals.

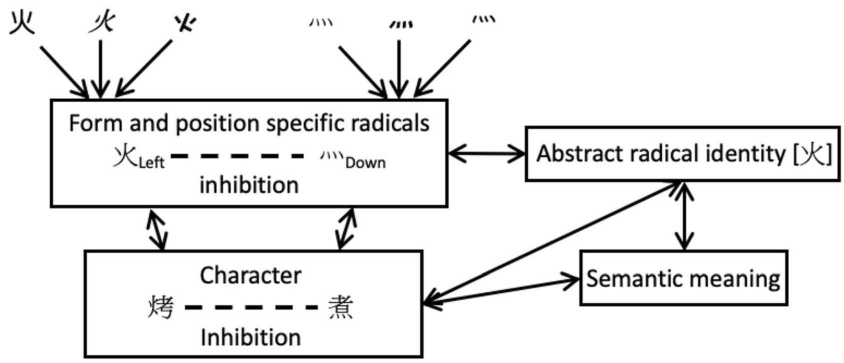

Fig. 7 Integration of radical identity recognition within the larger context of character recognition, expanding upon Ding et al. (2004)

Additional approaches to evaluating the ARI hypothesis

The analysis of Experiment 1 data assumed that the semantic similarity of the radical pairs was linearly related to reaction time; and, similarly, the analysis of Experiment 2 data assumed that the semantic similarity between the primes and targets was also linearly related to reaction time. On this basis, linear effects modelling was used to distinguish the contribution of semantics from the ARI effect. Critically, the results of these analyses provided support for the claim that the ARI effect could not be reduced to a semantic effect. However, if these assumptions do not hold and, for example, if reaction times increase exponentially with semantic similarity or if 100% semantic overlap (as occurs for same-radical/different-form pairs) is nonlinearly related to the lesser degrees of semantic overlap that were evaluated, the conclusions drawn from these key analyses could be undermined. Apart from behavioral studies, neuroimaging studies may also provide evidence regarding the hypothesis that ARI effects are not simply reducible to semantic effects. Using RSA (representational similarity analysis), Rothlein and Rapp (2014) provided neural evidence that the left fusiform gyrus had similar representations for letters that have the same identity, but different case. More importantly, the similarity of the neural response patterns could not be explained by visual, motor, or phonetic similarity. This evidence supports the role of the left fusiform gyrus in representing abstract submorphemic units. Along these lines, if the representations of radicals with same identity/different form were found to have similar neural representations in the left fusiform gyrus or elsewhere that could not be attributed to semantic similarity, then this would further support the existence of ARIs by spatially distinguishing the representation of semantics and ARI in the brain. Another similar approach would be to use RSA-EEG/RSA-MEG to identify if there is temporal segregation of the ARI and the semantic effects (Kaneshiro, Guimaraes, Kim, Norcia, & Suppes, 2015; Wang et al., 2020).

Conclusions

To conclude, evidence from same–different judgment and lexical decision priming tasks supports the conclusion that the radical in Chinese orthography has an abstract form-invariant representation. Many questions remain including, importantly, how these representations interact with semantic and phonological representations. It seems clear, however, that abstract orthographic component information is used in the recognition of Chinese characters.

Compliance with ethical standards

Data and materials for all experiments are available (https://osf.io/526xv/?view_only=e167d1bd3de343ae8c6c494451a2a1c6), and none of the experiments was preregistered.

Conflicts of interest We have no conflicts of interest to disclose.

Appendices

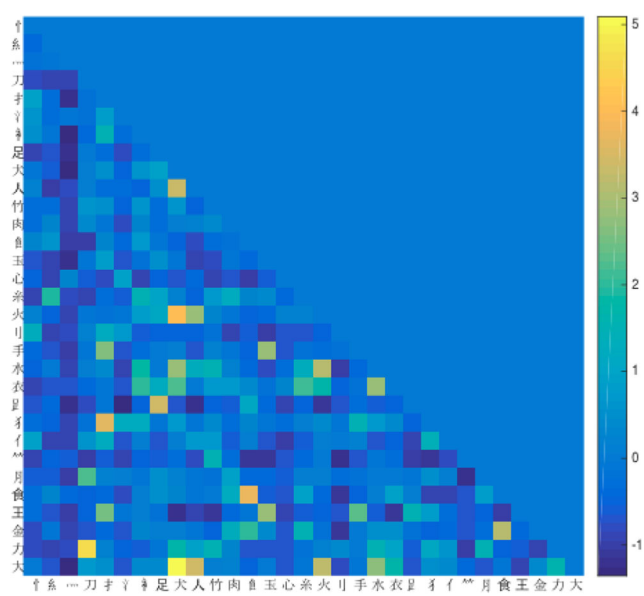

Fig. 8 Similarity matrix of visual similarity judgement. Darker color means lower similarity; lighter color means higher similarity

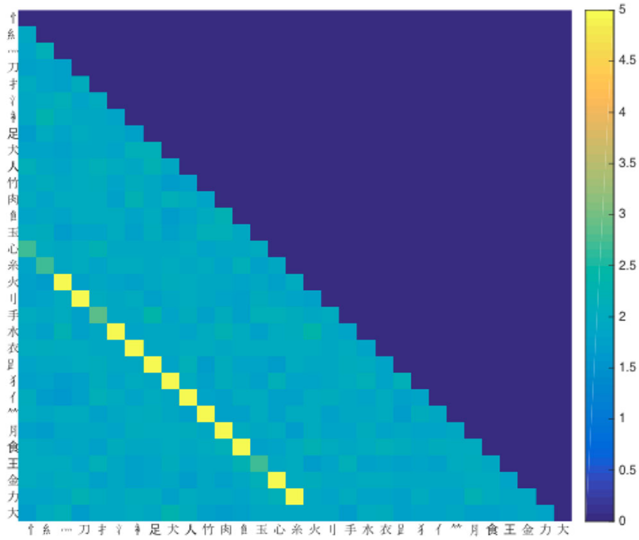

Fig. 9 Similarity matrix of sematic similarity judgement. Darker color means lower similarity; lighter color means higher similarity

Table 7 Results of reaction time LMEM for 55-ms SOA

	Estimate	*SE*	*t* value	Confidence interval	VIF
(Intercept)	6.33	0.03	200*	[6.2, 6.4]	1
SR/DF vs. DR/DF^{-SEM}	0.06	0.01	4.4*	[0.03, 0.09]	1
DR/DF^{+SEM} vs. DR/DF^{-SEM}	0.02	0.01	1.65	[−0.003, 0.04]	1
Pixel overlap	0.01	0.01	2.4*	[0.002, 0.02]	1
Previous trial accuracy	0.01	0.02	0.8	[−0.02, 0.05]	1
Number of strokes in target	0.01	0.01	2.9*	[0.005, 0.03]	1
Number of strokes in prime	0.01	0.01	0.2	[−0.01 0.01]	1
Spatial configuration	0.04	0.01	3.8*	[0.02, 0.06]	1
Prime character frequency	0.01	0.01	1.4	[0, −0.02]	1
Target character frequency	−0.02	0.01	−2.9*	[−0.03, −0.005]	1
Radical frequency	−0.01	0.01	−1	[−0.02, 0.004]	1
Number of strokes shared by prime and target	−0.01	0.01	−1.8	[−0.02, 0]	1
Prime–target character semantic similarity	−0.01	0.01	2.4*	[−0.02, 0]	1

**p* < .05

Table 8 Results of reaction time LMEM for 200ms SOA

	Estimate	*SE*	*t* value	Confidence interval	VIF
(Intercept)	6.32	0.04	163*	[6.2, 6.4]	
SR/DF vs. DR/DF^{-SEM}	0.05	0.01	3.2*	[0.02, 0.07]	1
DR/DF^{+SEM} vs. DR/DF^{-SEM}	0.02	0.01	1.5	[0, 0.04]	1
Pixel overlap	0.003	0.01	0.6	[0, 0.1]	1
Previous trial accuracy	0.01	0.02	0.5	[−0.03, 0.1]	1
Number of strokes in target	0.01	0.01	2.1*	[0, 0.02]	1
Number of strokes in prime	0	0.01	−1.6	[−0.02, 0]	1
Spatial configuration	0.04	0.01	3.7*	[0.02, 0.07]	1
Prime character frequency	0.01	0.01	1.3	[0, 0.02]	1.2
Target character frequency	−0.02	0.01	−2.7*	[−0.03, −0.01]	1
Radical frequency	0	0.01	−0.1	[−0.01, 0.01]	1
Number of strokes shared by prime and target	0	0.01	−1.6	[−0.02, 0]	1
Prime–target character semantic similarity	−0.01	0.01	−2.4*	[−0.01, 0.04]	1.2

**p* < .05

Table 9 Results of accuracy GLM for 55-ms SOA

	Estimate	*SE*	*t* value	VIF
(Intercept)	6.9	2.1	3.3*	
SR/DF vs. DR/DF^{-SEM}	−5.6	2.6	2.1**	2.4
DR/DF^{+SEM} vs. DR/DF^{-SEM}	−4.1	2.1	2	2.4
Pixel overlap	−0.7	0.5	−1.5	1.7
Previous trial accuracy	0.8	0.7	1.1	1
Number of strokes in target	−0.5	0.5	−0.9	2.2
Number of strokes in prime	−0.2	0.5	−0.4	1.6
Spatial configuration	0.7	0.8	0.9	1.6
Prime character frequency	−0.3	0.8	−0.5	2.2
Target character frequency	1.5	0.9	1.6	1.4
Radical frequency	−0.8	0.8	−0.9	3.4
Number of strokes shared by prime and target	0	0.4	0.04	1.5
Prime–target character semantic similarity	−0.2	0.4	−0.4	1.2

**p* < .05, ***p* < .10

Table 10. Results of accuracy GLM for 200ms SOA

	Estimate	*SE*	*t* value	VIF
(Intercept)	22	38	0	
SR/DF vs. DR/DF^{-SEM}	−1.4	1.2	−1.2	1.7
DR/DF^{+SEM} vs. DR/DF^{-SEM}	−0.2	0.8	0.8	1.7
Pixel overlap	−0.2	0.6	−0.3	1.7
Previous trial accuracy	−17	38	0	1
Number of strokes in target	0.01	0.01	1.59	1.9
Number of strokes in prime	0.4	0.5	0.8	1.9
Spatial configuration	−0.1	0.7	−0.2	1.4
Prime character frequency	0.3	0.8	0.3	1.5
Target character frequency	2.3	1.3	1.7	1.4
Radical frequency	−0.4	0.6	−0.7	2.1
Number of strokes shared by prime and target	0.8	0.4	1.9	1.9
Prime–target character semantic similarity	0.5	0.5	0.9	1.4

**p* < .05

Table 11 Stimulus pairs used in Experiment 1

SR/SF		SR/DF	DR/DF			
足-足	⻊-⻊	足-⻊	火-水	手-⻊	氵-扌	刀-亻
飠-飠	食-食	飠-食	衣-食	糹-玉	大-扌	氵-足
竹-竹	⺮-⺮	竹-⺮	手-月	灬-⺩	力-衣	氵-肉
扌-扌	手-手	扌-手	刀-力	人-竹	忄-犭	衤-人
忄-忄	心-心	忄-心	犬-大	糹-玉	犬-人	衤-心
人-人	亻-亻	人-亻	扌-刂	月-⺩	扌-犭	糸-食
氵-氵	水-水	氵-水	肉-玉	亻-⺮	水-糸	⺮-飠
衤-衤	衣-衣	衤-衣	飠-衣	飠-火	衤-月	糸-刂
糹-糹	糸-糸	糹-糸	肉-糸	⻊-食	氵-犭	⺩-心
刀-刀	刂-刂	刀-刂	竹-食	手-⺮	大-⻊	灬-足
犬-犬	犭-犭	犬-犭	足-人	心-手	犭-亻	力-衤
玉-玉	⺩-⺩	玉-⺩	氵-心	忄-衣	食-水	忄-竹
肉-肉	月-月	肉-月	食-月	大-刀	犬-力	力-糹
灬-灬	火-火	灬-火	人-大	灬-水	火-足	忄-刀

Table 12 Prime–target pairs used in Experiment 2

SR/DF			DR/DF^{+SEM}			DR/DF^{-SEM}		
刷-切	例-傘	拴-拳	愈-血	裝-館	緣-理	況-他	到-忘	絡-爹
繳-索	汰-泵	據-掌	慣-肝	揣-肢	琶-貴	瑟-滑	繪-侄	脹-剃
煞-煌	沒-漿	狀-狙	懲-拿	措-體	脫-皮	俱-劣	抒-貧	候-索
令-伸	刊-刃	裕-裳	括-怒	擅-距	肯-飾	損-熊	脆-統	捐-針
裝-被	劑-分	裂-衫	燕-淘	今-快	現-恆	何-根	恰-剩	衷-勺
累-終	副-剪	災-烹	然-沿	併-把	理-礦	倍-蝴	以-緩	低-泵
侖-倔	券-割	怎-快	前-捕	假-技	裨-服	瑞-訪	褐-釣	狙-素
余-你	括-拿	縣-細	劉-衫	值-物	膠-牛	裡-佳	恩-館	繳-柴
仟-倉			剩-捱			無-桂		

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