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Semantic radicals in Japanese two-character word recognition

Koji Miwa

Department of Linguistics, University of Alberta, Edmonton, Canada

Gary Libben

Department of Linguistics, University of Calgary, Calgary, Canada

R. Harald Baayen

Department of Linguistics, University of Alberta, Edmonton, Canada

Address for correspondence:

Koji Miwa

4-32 Assiniboia Hall, Department of Linguistics

University of Alberta, Edmonton, Alberta, T6G2E7 Canada

E-mail: kmiwa@ualberta.ca, Phone: +1(780)492-3434, FAX: +1(780)492-0806

Abstract

Extending previous studies on sub-lexical character constituent activation in Japanese and Chinese, the present regression study investigates whether recognition of two-character words in Japanese involves activation of semantic radicals and whether the semantic radicals' contribution is orthographic or semantic in nature. A mixed-effects model complemented with a random forest analysis provided support for the importance of the semantic radical, as witnessed by two orthogonal sets of semantic radical properties: the radicals' semantic transparency and usefulness, as well as the semantic radicals' combinability and token frequency. The two frequency effects were facilitatory for the head of the compound, but inhibitory for the modifier, possibly due to incompatibility of the semantic class marked by the modifier's radical with that of the compound as a whole. Thus, semantic radicals emerge as not just orthographic components but as fully-fledged purely orthographic morphemes.

Semantic radicals in Japanese two-character word recognition

Research on morphological processing suggests that complex words are not recognized simply by full-form-to-meaning matching nor are they recognized only through feed-forward combinatorial computations (Bertram, Baayen, & Schreuder, 2000; Frost, Grainger, & Carreiras, 2008; Frost, Grainger, & Rastle, 2005; Libben, 1998; Rastle, Davis, & New, 2004; Taft & Kougious, 2004). Instead, both computational efficiency and storage efficiency seem to be optimized simultaneously (e.g., Kuperman, Schreuder, Bertram, & Baayen, 2009; Libben, 2006).

This optimization of storage and computation should also apply to reading of Japanese and Chinese, languages with a morphographic writing system. In these languages, a large majority of words is represented orthographically by means of two complex characters. There is clear evidence for character activation in the recognition of two-character words (see Joyce 2002; Kawakami, 2002; Tamaoka & Hatsuzuka, 1995, 1998 for Japanese, and Huang, Lee, Tsai, Hung, & Tzeng, 2006; Ji & Gagné, 2007; Zhou, Marslen-Wilson, Taft, & Shu, 1999 for Chinese). Tamaoka and Hatsuzuka (1995) reported that, independently of whole word frequency, the right character's frequency speeds up responses in a two-character word lexical decision. Effects of characters' meanings (Tamaoka & Hatsuzuka, 1998) and an effect of the conceptual relation governing the interpretation of two character compounds (Ji & Gagné, 2007) suggest that, as expected, the characters in a two-character compound mediate lexical processing. However, no study on two-character word recognition has assessed the contribution of sub-morphemic components, the orthographic morphemes unique to morphographic orthography known as semantic radicals.

A majority of characters are composed of two radicals: a *semantic radical*, a semantic constituent encoding a basic category meaning, and a *phonetic radical*, a phonological constituent. Phonetic radical activation was witnessed in studies addressing the processing of single-characters (Hsu, Tsai, Lee, & Tzeng, 2009; Lee, Tsai, Huang, Hung, & Tzeng, 2006). The present study focuses on the role of semantic radicals. Semantic radicals function as entries in character dictionaries. They also provide useful classification cues in learning the 1,006 characters taught in primary education (Ministry of Education, Culture, Sports, Science and Technology, 2009).

Experimental evidence for semantic radical activation comes from single-character decision (Feldman & Siok, 1997 on Chinese), single-character decision with priming (Feldman & Siok, 1999 on Chinese), speeded single-character semantic-categorization (Flores d'Arcais & Saito, 1993 on Japanese), and single-character word naming (Flores d'Arcais, Saito, & Kawakami, 1995 on Japanese). Previous research has shown that characters with a semantic radical occurring in many other characters are read faster. Taft and Zhu (1997) and Saito (1997) assume that semantic radicals play a similar role in the reading of two-character words. As we shall see this assumption is only partially validated by our study, which addresses the role played by semantic radicals in the ecologically important context of two-character words. More specifically, the present study seeks to clarify whether the effects of semantic radicals depend on their position in the left (modifier) versus the right (head) character. We also aim to clarify the role of the semantic transparency of semantic radicals, and to establish the extent to which radical type frequency effects are independent of age of acquisition (AoA, see, e.g., Juhasz, 2005). Finally, we investigate how the commonly-used partial priming manipulation affects complex word recognition.

We implemented an analysis of covariance design, combining several numerical predictors with a factorial treatment, overt priming, as most studies addressing lexical processing in Japanese and Chinese using behavioral measures made use of priming manipulations (see Feldman & Siok, 1999; Joyce, 2002). For the statistical analysis, we made use of a mixed-effects model complemented by random forests (a conditional inference tree-based ensemble method, see, e.g., Strobl, Boulesteix, Kneib, Augustin, & Zeileis, 2008; Strobl, Malley, & Tutz, 2009). This combined approach allows us to evaluate both significance and magnitude of semantic radicals' contribution to response speed relative to the contribution of character and whole word properties.

Method

Participants

Thirty native speakers of Japanese (23 females, mean age = 28.5, *SD* = 7.9) were recruited as paid participants at the University of Alberta and neighboring cities in Alberta, Canada.

Apparatus

The experiment was run with PsyScope (Cohen, MacWhinney, Flatt, & Provost, 1993) using a Macintosh iMac computer and an iBook computer operating under OS 9.2. The *S* and *L* keys on a Macintosh keyboard were used for lexical decision responses.

Materials

Forty-six prime-target pairs of two-*kanji* words were constructed. Prime and target pairs shared the semantic radical of their right character, as previous research has shown that the right character, the head, co-determines lexical decision latencies to a greater extent than the left character (Libben, Gibson, Yoon, & Sandra, 2003; Tamaoka & Hatsuzuka, 1995). Forty-six two-character pseudo-homophonous nonwords were prepared by replacing the first character of existing two-character words by another existing homophonic character. We divided the 46 critical word pairs into two sets (A and B) of 23 word pairs each. One group of participants was presented with the words of set A paired with primes sharing the semantic radical, with the words from set B paired with control primes that did not share the radical. A second group of participants was presented with the words from set B paired with primes sharing the right semantic radical and the words from set A paired with non-matching control primes. During the experiment, therefore, participants encountered 92 stimuli in total: 23 primed pairs, 23 control pairs, and 46 nonwords (See Table 1). A given word was presented only once to a given participant. Mean semantic similarity, gauged by LSA scores (Landauer, Foltz, & Laham, 1998) for the translated prime-target pairs, was 0.07 for both primed and unprimed conditions [$t(45) = 0.12$, $p = 0.91$].

(Table 1 about here)

Procedure

A trial consisted of a fixation point (*) presented at the centre of the display for 1,000 ms, followed by a 230 ms prime, followed by a backward mask (##) of 200 ms to avoid visual-overlap effects, after which the target word appeared and remained on the screen until participants responded by pressing one of two keys on the keyboard. Participants were instructed to decide, as quickly and accurately as possible, whether the second word (i.e. the target) is an existing word in Japanese by pressing the *L* key for words and *S* key for nonwords. The prime word was always an existing two-character word. Fixation point and masks were presented in Times New Roman 48, and words in Mincho 48.

Results

Statistical analyses in this study were carried out by using `R` version 2.9.2 (R Development Core Team, 2009). One participant with 43% error rate was excluded from the data analysis. Stimuli that elicited RTs shorter than 300 ms or longer than 3,000 ms were also excluded (8 data points). Furthermore, four target words that elicited more than 30% error rate (113 target data points, 8.5% of the data) were excluded from the analysis. The mean error rate for the remaining 1,213 target responses was 8% (1,121 correct, 92 incorrect). For these 1,213 data points, the quantiles of the target error rates were 0% (minimum), 0% (1st quartile), 5% (median), 14% (3rd quartile), and 28% (maximum). The corresponding quantiles of the subject error rates were 0% (minimum), 5% (1st quartile), 5% (median), 12% (3rd quartile), and 26% (maximum). A reciprocal transformation was applied to RTs (-1000/RT) to remove the skew characterizing the distribution of the raw RTs. Only correct responses, 1,121 data points, were considered for the response time analyses. All predictors with a noticeably skewed distribution were logarithmically transformed.

(Table 2 about here)

Table 2 lists the predictors in our model, ordered by linguistic levels. At the level of radicals, the level of our primary interest, previous studies have shown that radicals used across many characters are processed faster (Feldman & Siok, 1997, 1999; Taft & Zhu, 1997). Following the terminology used by Feldman and Siok (1997, 1999), radical combinability counts (*LogLeftKanjiRadicalCombinability, LogRightKanjiRadicalCombinability*) represent the type count of basic *kanji* characters sharing a given semantic radical with any of the other 1,945 basic *kanji* characters. Radical token frequency measures (*LogLeftKanjiRadicalTokenFreq, LogRightKanji*

RadicalTokenFreq) represent the cumulative token frequency of the *kanji* characters sharing a given semantic radical (Tamaoka, Kirsner, Yanase, Miyaoka, & Kawakami, 2002; Yokoyama, Sasahara, Nozaki and Long, 1998).

Three further radical measures were considered: the position of the semantic radical in the right character (*RightKanjiRadicalPosition*, *left* vs. *other*) and type frequency of the non-semantic radical in the right character (*LogRightKanjiOtherRadicalFreq*, Saito, Kawakami, & Masuda, 1995, 1997). Finally, we considered a factor distinguishing between prime-target pairs sharing the semantic radical in the same position and those in which the semantic radical appeared at different positions (*PrimeTargetRadicalPositionConsistency*). The positional measures did not reach or even approach significance in our analysis (see also Figure 2), and hence will not be reported below.

We obtained two semantic measures for the right *kanji* radicals. *RightKanjiRadicalTransparency* is a measure based on twenty-one native Japanese readers' evaluation on a seven-point scale of the congruity between the meaning of the character and the meaning of the component radical. *RightKanjiRadicalUsefulness* gauges how useful a given semantic radical is in predicting the character meaning. Thirty native Japanese readers were given a sheet of paper with single-characters with their semantic radical portion visible and all other portions ink-blobbed. This task measured the independent meaningfulness of semantic radicals. The rating scores in *RightKanjiRadicalTransparency* and *RightKanjiRadicalUsefulness* were significantly correlated ($r = 0.53$, $p < 0.01$). Since the reliability of the semantic information provided by a given semantic radical varies across the characters of the language, we expect that semantic radicals with greater independent meaningfulness play a more substantial role in reading.

As predicted at the level of features, we encoded constituent complexity using stroke counts (*PrimeRightKanjiStrokes, LeftKanjiStrokes, LeftKanjiRadicalStrokes, RightKanjiStrokes, RightKanjiRadicalStrokes*). At the character level, we considered written token frequency (Amano & Kondo, 2003) for the left and right characters of target words (*LogRightKanjiTokenFreq, LogLeftKanjiTokenFreq*) and for the right character of the prime words (*LogPrimeRightKanjiTokenFreq*) whose semantic radical is the target of the present the priming manipulation. The character neighbour measures (*LogPrimeRightKanjiNeighbour, LogLeftKanjiNeighbour, LogRightKanjiNeighbour*) represent a given character's position-specific morphographic family size (Joyce & Ohta, 2002). Our age of acquisition (AoA) measures (*PrimeRightKanjiAoA, LeftKanjiAoA, RightKanjiAoA*) represents the school grades at which the characters in our prime and target words are first taught. They are an objective measure for AoA. Lastly, we considered the token frequency of the whole word (*LogWholeWordTokenFreq,* Amano & Kondo, 2003).

Given substantial multicollinearity, we made use of two statistical techniques: the parametric technique of mixed effects modeling with orthogonalization of predictors through a principal component analysis (PCA, Belsley, Kuh, & Welch, 2004) and a non-parametric technique, random forests.

Principal components regression analysis

Principal component orthogonalization was applied separately to the eighteen target word properties and to the five prime word properties. We then selected those PCs that accounted for at least 5% of the variance. Among target PCs, the top seven PCs cumulatively accounting for 84.1% of the variance (See Table 2). For the prime PCs, the three accounted for 88.4% of the variance. These PCs were entered as predictors in a mixed-effects analysis of covariance (Baayen, Davidson, & Bates, 2008; Bates, Maechler, & Dai, 2007). A backward stepwise variable selection procedure identified five target PCs as significant: PC1, PC3, PC4, PC5, and PC7.

Table 3 lists the estimate, standard error, upper and lower limits of Highest

Posterior Density (HPD) confidence interval, as well as t-values and p-values based on Markov chain Monte Carlo (MCMC) sampling for these five PCs. Each PC's contribution is visualized in Figure 1. In order to clarify the nature of the PCs, we inspected the loadings of the original lexical predictors on these PCs. Table 2 presents the predictors with the largest loadings in bold (the predictors with high loadings exceeding 0.30 or smaller than -0.30 are shown in bold). In our discussion, we highlight only those predictors that have the greatest loadings and carry the main trends. We will complement this discussion with a random forests analysis that evaluates the contribution of individual predictors in a non-parametric way.

(Table 3 about here)

(Figure 1 about here)

The inhibitory predictor PC1 (Figure 1 panel a), effect size (range) 218 ms, quantifies primarily the combinability and token frequency of the right character's semantic radical (*LogRightKanjiRadicalCombinability* and *LogRightKanjiRadicalTokenFreq*). Since these predictors correlate negatively with an inhibitory PC, their effect on RTs is facilitatory. Right characters that contain a semantic radical with high combinability or high token frequency are read faster. In contrast to the above facilitatory predictors, *RightKanjiAoA* loaded positively on PC1 and hence their effects on RTs are inhibitory. Words with a character that has been taught at a later age are read less quickly, as expected.

PC3 is a facilitatory predictor (panel b, effect size 111 ms). Both *LogWholeWordTokenFreq* and *LogRightKanjiTokenFreq* loaded positively on PC3 (see Table 2) and hence indicate facilitation. *LeftKanjiRadicalStroke* has a large negative loading on PC3, indicating increasing RTs with increased orthographic complexity of the semantic radical of the left character.

PC4 is an inhibitory predictor (panel c, effect size 254 ms), and it is characterized by *LeftKanjiStrokes* and *LogLeftKanjiRadicalCombinability*, which have the largest positive loadings, indicating inhibition. The inhibitory effect of *LogLeftKanjiRadicalCombinability* on the RTs contrasts with the facilitatory contribution of the right character's semantic radicals as witnessed by the effects of *LogRightKanjiRadicalCombinability* and *LogRightKanjiRadicalTokenFreq* loading on PC1.

As shown in panel d, PC5 speeded up responses in the primed condition (effect size 38 ms) but slowed down responses in the unprimed control condition (effect size 61 ms). PC5 is characterized by large negative loadings of the semantic radical properties, *RightKanjiRadicalTransparency* and *RightKanjiRadicalUsefulness*. In the unprimed control condition, characters with a semantically more transparent and more useful radical elicited shorter response latencies. This pattern reverses when a related prime is presented. In other words, target words with radicals with low transparency and usefulness benefit more from the priming manipulation.

We note here that a main effects model with just the priming manipulation as predictor yielded a facilitatory effect of priming (mean RT control 718 ms, mean RT primed 703 ms, effect size 15 ms) that just failed to reach significance at $\alpha = 0.05$ ($p = 0.0570$ using Markov chain Monte Carlo sampling, $p = 0.0501$ using the upper bound for the degrees of freedom for the t-test). Importantly, our analysis of covariance allowed us to clarify that the priming effect is indeed a semantic effect, as expected for semantic radicals. Furthermore, the analysis of covariance also clarified that the priming effect increased for decreasing transparency of semantic radicals. Finally, the analysis of covariance also allowed us to bring the priming effect into perspective with respect to other distributional predictors: compared to the other predictors in our model, the effect size of the priming manipulation is modest.

The effect of PC7 was inhibitory (effect size 187 ms). Since the loadings on PC7 are dominated by *LogRightKanjiOtherRadicaTypeFreq* (0.64), PC7 represents an inhibitory effect of type frequency of the non-semantic radical component. This inhibitory effect of the non-semantic radical contrasts with the facilitation observed for the frequency of the semantic radical represented by PC1 (*LogRightKanjiRadicalCombinability* and *LogRightKanjiRadicalTokenFreq* have negative loadings on PC1). This result supports theories that distinguish between semantic and non-semantic radicals (e.g., Feldman & Siok, 1997, 1999).

The position of the semantic radical in the right character (*RightKanjiRadicalPosition*) was not predictive. Similarly, the factor specifying whether the radical occupied the same position across prime and target (*PrimeTargetRadicalPositionConsistency*) failed to reach significance as well. This allows us to conclude that the priming effect is semantic in nature and was not driven by positional overlap.

Prime PCs, representing the properties of the prime words, as well as participants' characteristics (i.e., age, sex, months of stay in Canada), did not emerge as significant predictors. We also investigated whether words with different ON(Chinese-origin)-KUN(Japanese-origin) pronunciations affected the results. Removal of the relevant words and re-analyses did not change the results.

Random forests analysis

Our regression model does not inform us about the specifics of the relative importance of the individual lexical variables that loaded onto various PC. For example, *RightKanjiRadicalTransparency* and *RightKanjiRadicalUsefulness* have very similar loadings on PC5, and their individual contributions cannot be teased apart. Furthermore, *LogWholeWordTokenFrequency* has high loadings on three PCs (PC3, PC4, and PC7) and hence its contribution is larger than one would expect on the basis of inspection of individual PCs. In order to obtain better insight into the relative importance of the individual variables, we made use of a random forests recursive partitioning method, a technique particularly useful for assessing a large number of predictors with small samples (*small n large p* problem, see Strobl, Malley, & Tutz, 2009). Conditional inference trees are grown for subsets of observations and subsets of predictors. Predictions are obtained by an ensemble method in which the votes of individual trees are collected. Variable importance is gauged by evaluating reduction in prediction accuracy when a given predictor is not considered (Breiman, 2001; Strobl, Boulesteix, Zeileis, & Hothorn, 2007).

Variable importance rankings (using the conditional permutation scheme proposed by Strobl, Boulesteix, Kneib, Augustin, & Zeileis, 2008, implemented in the `cforest` function in the `party` package of Hothorn, Buehlmann, Dudoit, Molinaro, & Van Der Laan, 2006; Strobl, Boulesteix, Kneib, Augustin, & Zeileis, 2008; Strobl, Boulesteix, Zeileis, & Hothorn, 2007) for the random forests fitted separately to the primed and the control conditions are shown in Figure 2. Basically, the variable importance plotted on the horizontal axes is a measure of the drop in prediction accuracy when the predictor is withheld from the model specification. For important predictors, failure to include them results in a large loss of prediction accuracy. For irrelevant factors, on the other hand, it does not matter when they are not included in the model specification.

(Figure 2 about here)

Figure 2 reveals a pattern consistent with the PCA regression analysis. *LogWholeWordTokenFreq* is identified, as the most important variable, which dovetails well with the observation that *LogWholeWordTokenFreq* has high loadings on several different PCs. The next most important variable is the token frequency of the right character (*LogRightKanjiTokenFreq*) in both primed and control conditions. The right character's importance in lexical decision is consistent with the result of Tamaoka and

Hatsuzuka (1995). While the PCA did not distinguish between contributions of semantic radical combinability and cumulative token frequency, the random forests analysis suggests that token frequency (*LogRightKanjiRadicalTokenFreq*) is more important than combinability (*LogRightKanjiRadicalCombinability*) in the unprimed condition. Note that *RightKanjiRadicalTransparency* and *RightKanjiRadicalUsefulness* are ranked higher in the primed condition, further confirming that, in the primed condition, the properties of the semantic radical afforded a processing advantage. Note that, as in the regression analysis, the positional predictors *RightKanjiRadicalPosition* and *PrimeTargetRadicalPositionConsistency* were irrelevant. Finally, *LogRightKanjiOtherRadicaTypeFreq* ranks among the top half of the importance ranked predictors.

General discussion

We identified several graded effects of semantic radical properties in two-character *kanji* word recognition in addition to the effects of character frequency and whole word frequency. Interestingly, the effect of a semantic radical's type and token frequencies depends on its position in the two-character word: inhibitory in modifier position and facilitatory in head position. This suggests that the facilitation observed in single-character studies does not generalize straightforwardly to the modifier position in two-character words. This asymmetrical effect of radical frequency was not modulated by the priming manipulation, which emerged only in interaction with *RightKanjiRadicalTransparency* and *RightKanjiRadicalUsefulness*. The facilitation characterizing heads and the inhibition observed for modifiers may be due to the semantic radical functioning as a kind of classifier. The semantic class indicated by the semantic radical of the head is congruent with that of the compound as a whole. For the modifier, by contrast, the semantic class indicated by its semantic radical is at odds with that of the compound as a whole.

Turning to this interaction, which expressed itself on PC5 in our PCA regression model, we observed facilitation for words with a right semantic radical with lower values on either semantic measure. This suggests that semantic radicals are not mere orthographic units but orthographic morphemes combining form and meaning properties. Random forests clarified that *RightKanjiRadicalTransparency* is more predictive than *RightKanjiRadicalUsefulness*, suggesting that the compositional part-whole relation between a semantic radical and its character is more influential in a visual lexical decision task than the intrinsic semantic richness of this radical.

In the PCA regression, AoA loaded on the same principal component as semantic radical type and token frequencies. Random forests analysis indicated that *LogRightKanjiTokenFreq* and *LogLeftKanjiTokenFreq* outperformed *RightKanjiAoA* and *LeftKanjiAoA* respectively in both priming conditions. Nevertheless, random forests analysis indicates that AoA is a robust predictor. Note that the random forest, using a measure of AoA which is not based on human ratings or performance but on the age at which characters are learned in school, replicates the finding that the frequency effect cannot be reduced to AoA (cf. Brysbaert, Lange, & Wijnendaele, 2000; Morrison & Ellis, 2000).

The present results indicate that describing the reading of two-character words as analogous to alphabetic compound word processing still underestimates the orthography-specific morphographic complexity of reading in Japanese. *Kanji* characters are themselves morphologically complex. The semantic radical can be viewed as a purely orthographic morpheme, combining a visual form with rich semantics, without support from a phonological/acoustic form. The experimental fingerprint of the semantic radical emerging from our study resembles in many ways the experimental fingerprint of standard morphemes as observed for many European languages, with position-dependent effects, with graded effects of semantic transparency, with effects of AoA, and with greater combinability affording faster processing (see, e.g., Moscoso del Prado Martín et al., 2004). This suggests that in Japanese, the orthography provides an additional layer of morphological complexity to the already complex classificatory system provided by the spoken language.

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Table 1

Types of prime-target pairs used in the present study

Condition	Prime			Target			
	Word	Translation	Radical	Word	Translation	Radical	Shared
Primed	時計	*toke* ‘clock’	言 *gomben*	書記	*shoki* ‘scribe	言 *gomben*	Yes
Control	救急	*kinkyu* ‘emergency’	心 *kokoro*	書記	*shoki* ‘scribe	言 *gomben*	No
Nonword	印刷	*insatsu* ‘fireplace’	刂 *ritto*	渋症	*jusho* ‘N/A’	疒 *yamaidare*	No

Table 2

Eighteen original predictors of target words and their loadings on the seven target PCs. The * mark represents significantly influential predictors in the regression model summarized in Table 3. The bolded values represent relatively large loadings (exceeding 0.30 or smaller than -0.30).

Type	Predictors	PC1*	PC2	PC3*	PC4*	PC5*	PC6	PC7*
Stroke	LeftKanjiStrokes	0.05	-0.23	-0.13	**0.42**	0.04	**-0.39**	**-0.33**
Stroke	LeftKanjiRadicalStrokes	-0.03	-0.24	**-0.36**	-0.01	-0.19	**-0.44**	-0.16
Stroke	RightKanjiStrokes	0.28	0.09	0.04	**-0.33**	-0.25	-0.12	**-0.36**
Stroke	RightKanjiRadicalStrokes	**0.30**	0.09	0.24	-0.17	-0.29	-0.24	-0.07
Radical	LogLeftKanjiRadicalCombinability	0.06	0.22	0.27	**0.47**	0.21	-0.04	-0.27
Radical	LogLeftKanjiRadicalTokenFreq	-0.04	**0.41**	0.16	**0.33**	0.24	-0.13	-0.10
Radical	LogRightKanjiRadicalCombinability	**-0.38**	-0.01	-0.11	0.17	-0.22	0.23	-0.13
Radical	LogRightKanjiRadicalTokenFreq	**-0.38**	-0.10	-0.03	0.08	-0.20	0.31	0.00
Radical	LogRightKanjiOtherRadicalFreq	0.11	0.13	**0.30**	0.14	-0.19	-0.20	**0.64**
Radical	RightKanjiRadicalTransparency	0.03	0.17	-0.06	**0.31**	**-0.49**	0.25	-0.07
Radical	RightKanjiRadicalUsefulness	0.23	0.21	0.08	0.14	**-0.50**	0.12	-0.12
Character	LogLeftKanjiNeighbour	-0.19	**0.41**	-0.22	-0.15	-0.08	-0.20	0.13
Character	LogLeftKanjiTokenFreq	-0.22	**0.43**	-0.09	-0.17	0.10	-0.14	-0.14
Character	LeftKanjiAoA	**0.30**	**-0.34**	0.23	0.10	0.10	0.21	-0.01
Character	LogRightKanjiNeighbour	-0.29	-0.21	0.24	0.01	-0.23	-0.17	-0.12
Character	LogRightKanjiTokenFreq	-0.29	-0.14	**0.44**	-0.11	-0.07	-0.13	-0.08
Character	RightKanjiAoA	**0.33**	0.10	**-0.30**	-0.03	0.11	**0.31**	-0.13
Word	LogWholeWordTokenFreq	-0.09	0.10	**0.37**	**-0.33**	0.11	0.20	**-0.37**
Variance accounted for by each PC		0.23	0.16	0.13	0.11	0.09	0.07	0.05
Cumulative variance accounted for		0.23	0.39	0.52	0.63	0.72	0.79	0.84

Table 3

Influential principal components (PCs) with their estimate, standard error, upper and lower limits of HPD confidence interval, t-value and p-value based on 10,000 Markov chain Monte Carlo (MCMC) samples from the posterior distributions of the parameters.

	Estimate	Std.Error	HPD95lower	HPD95upper	t-value	pMCMC
(Intercept)	-1.3898	0.0389	-1.4550	-1.3247	-35.77	0.0001
TargetPC1	0.0428	0.0104	0.0242	0.0613	4.10	0.0001
TargetPC3	-0.0355	0.0138	-0.0110	-0.0603	-2.57	0.0064
TargetPC4	0.0789	0.0149	0.1052	0.0518	5.30	0.0001
TargetPC5	0.0227	0.0176	0.0539	0.0092	1.29	0.1482
Condition (primed)	-0.0322	0.0153	-0.0627	-0.0020	-2.10	0.0356
TargetPC7	0.0643	0.0217	0.0265	0.1033	2.97	0.0014
TargetPC5 by Condition (primed)	-0.0376	0.0130	-0.0134	-0.0642	-2.90	0.0034

Figure Captions

Figure 1. Partial effects of four influential principal components (PCs) on response latencies in the primed lexical decision. PC1: Larger right character semantic radical combinability/ token frequency (negative loadings on PC1) indicate shorter RTs (panel a); PC3: Larger word/ right character frequency (positive loadings on PC3) indicate shorter RTs (panel b); PC4: Larger left character semantic radical combinability/ token frequency (positive loadings on PC4) slow responses (panel c); PC5: Larger right character radical transparency/ usefulness (negative loadings on PC5) indicate shorter RTs in the control condition but longer RTs in the primed condition (panel d). PC7: Larger right character non-semantic radical type frequency (positive loadings on PC7) indicates longer RTs.

Figure 2. A random forest's variable importance ranking for the primed and the control conditions. Variable importance is assessed in terms of mean decrease in accuracy.

Figure 1

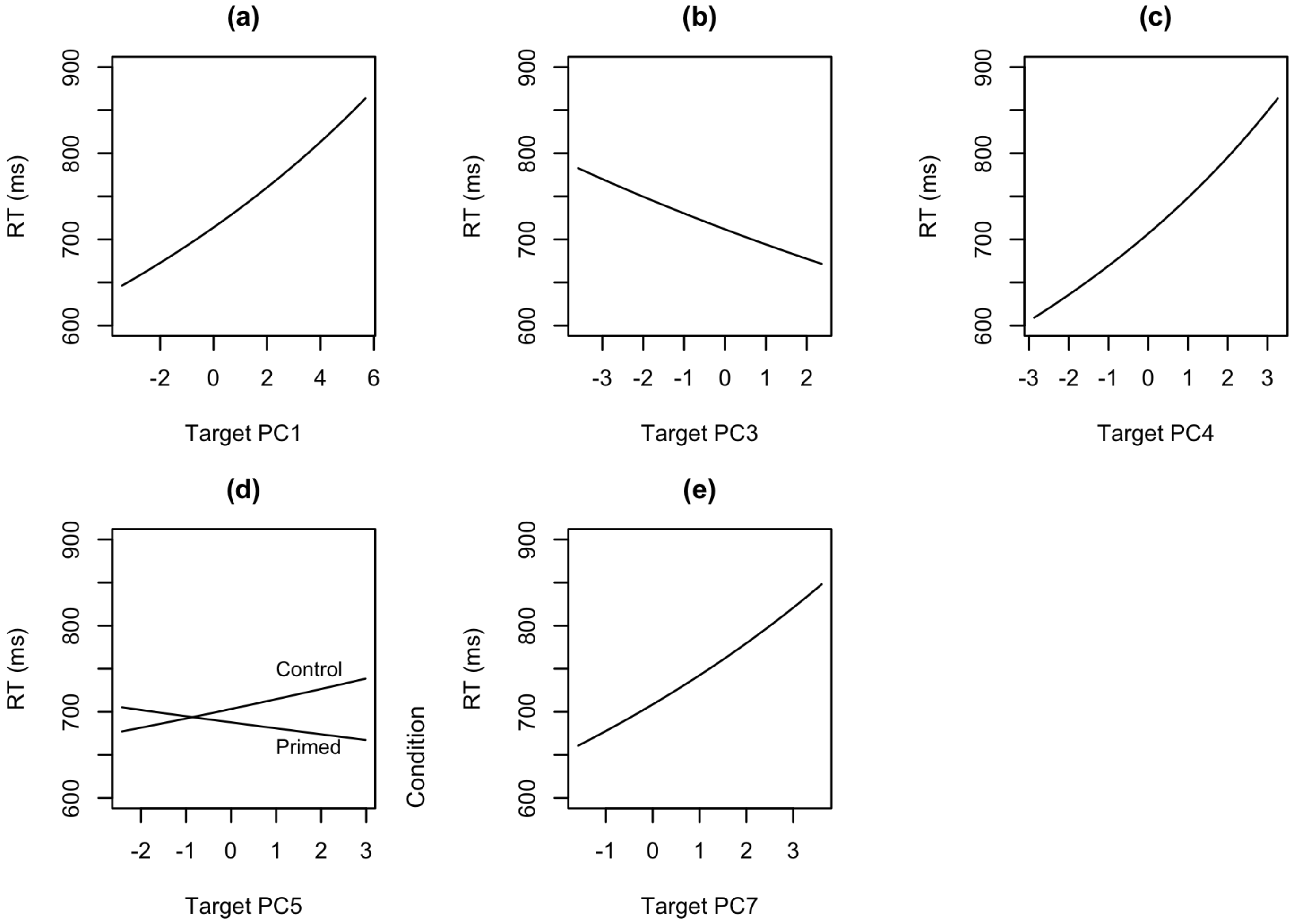
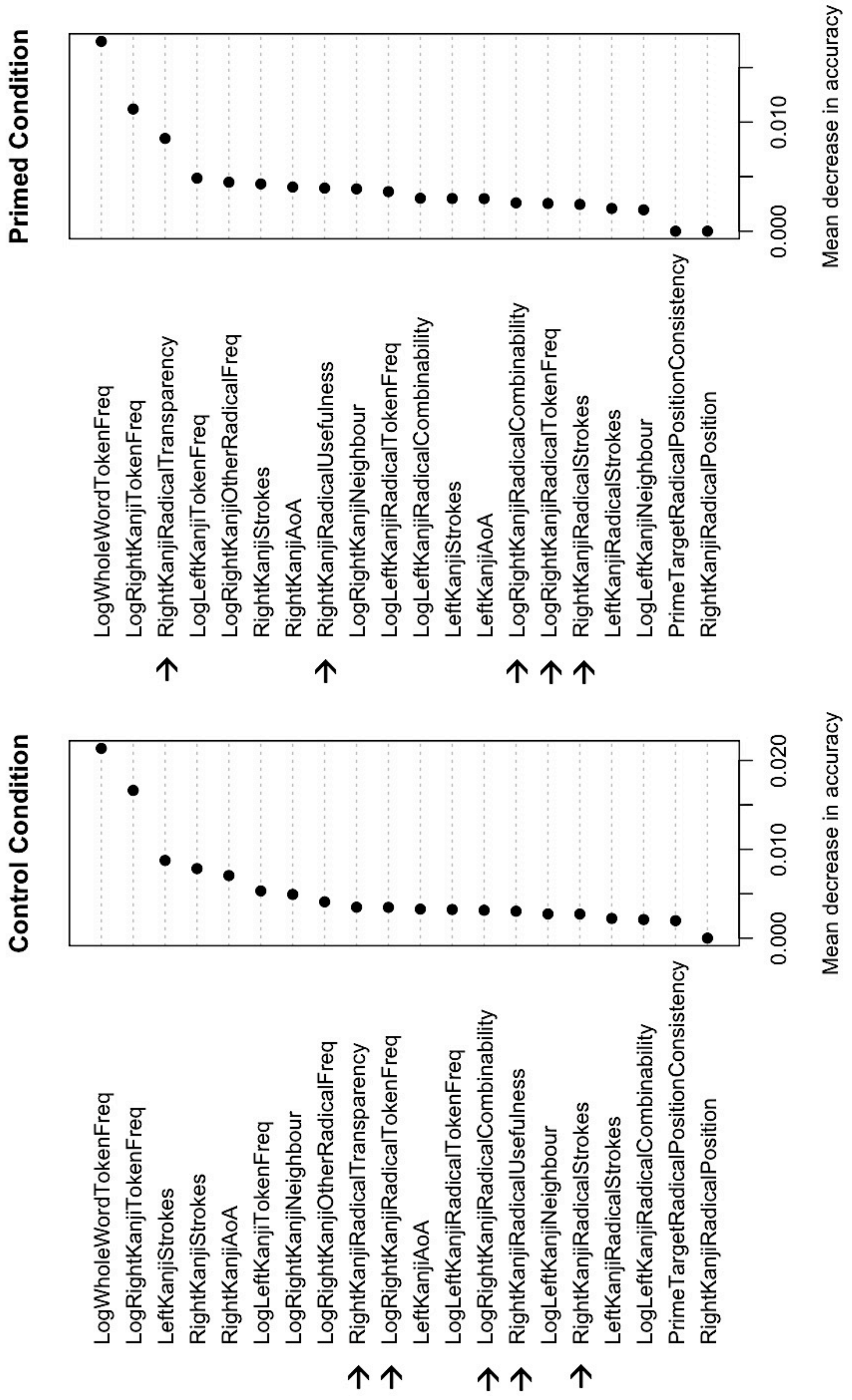

(a)
RT (ms)
600
700
800
900
-2
0
2
4
6
Target PC1
(b)
RT (ms)
600
700
800
900
-3
-2
-1
0
1
2
Target PC3
(c)
RT (ms)
600
700
800
900
-3
-2
-1
0
1
2
3
Target PC4
(d)
RT (ms)
600
700
800
900
Control
Primed
Condition
-2
-1
0
1
2
3
Target PC5
(e)
RT (ms)
600
700
800
900
-1
0
1
2
3
Target PC7

Figure 2


Primed Condition
LogWholeWordTokenFreq
LogRightKanjiTokenFreq
RightKanjiRadicalTransparency
LogLeftKanjiTokenFreq
LogRightKanjiOtherRadicalFreq
RightKanjiStrokes
RightKanjiAoA
RightKanjiRadicalUsefulness
LogRightKanjiNeighbour
LogLeftKanjiRadicalTokenFreq
LogLeftKanjiRadicalCombinability
LeftKanjiStrokes
LeftKanjiAoA
LogRightKanjiRadicalCombinability
LogRightKanjiRadicalTokenFreq
RightKanjiRadicalStrokes
LeftKanjiRadicalStrokes
LogLeftKanjiNeighbour
PrimeTargetRadicalPositionConsistency
RightKanjiRadicalPosition
0.000
0.010
Mean decrease in accuracy
Control Condition
LogWholeWordTokenFreq
LogRightKanjiTokenFreq
LeftKanjiStrokes
RightKanjiStrokes
RightKanjiAoA
LogLeftKanjiTokenFreq
LogRightKanjiNeighbour
LogRightKanjiOtherRadicalFreq
RightKanjiRadicalTransparency
LogRightKanjiRadicalTokenFreq
LeftKanjiAoA
LogLeftKanjiRadicalTokenFreq
LogRightKanjiRadicalCombinability
RightKanjiRadicalUsefulness
LogLeftKanjiNeighbour
RightKanjiRadicalStrokes
LeftKanjiRadicalStrokes
LogLeftKanjiRadicalCombinability
PrimeTargetRadicalPositionConsistency
RightKanjiRadicalPosition
0.000
0.010
0.020
Mean decrease in accuracy

APPENDIX

A list of word pairs used in the present study. Items marked with * were excluded from the final analyses based on error rate.

RadicalShared	CriticalPrime	CriticalTarget	RadicalShared	ControlPrime	ControlTarget
Yes	豆粒	妖精	No	薄味	妖精
Yes	救急	得意	No	家財	得意
Yes	犠牲	放牧	No	学校	放牧
Yes	反転	五輪	No	犠牲	五輪
Yes	時計	書記	No	救急	書記
Yes	旅館	*綿飴	No	教授	*綿飴
Yes	道路	跳躍	No	空港	跳躍
Yes	睡眠	明瞭	No	苦悩	明瞭
Yes	筆箱	縦笛	No	潔癖	縦笛
Yes	積荷	*国花	No	自爆	*国花
Yes	満点	高熱	No	車掌	高熱
Yes	自爆	*土煙	No	心霊	*土煙
Yes	釣針	手鏡	No	睡眠	手鏡
Yes	結婚	年始	No	積荷	年始
Yes	空港	血液	No	釣針	血液
Yes	家財	盗賊	No	道路	盗賊
Yes	薄味	合唱	No	時計	合唱
Yes	教授	薬指	No	反転	薬指
Yes	学校	球根	No	筆箱	球根
Yes	車掌	攻撃	No	豆粒	攻撃
Yes	心霊	落雷	No	満点	落雷
Yes	潔癖	治療	No	旅館	治療
Yes	苦悩	習慣	No	結婚	習慣
Yes	物価	同僚	No	海図	同僚
Yes	皆勤	援助	No	角度	援助
Yes	決闘	玄関	No	皆勤	玄関
Yes	樹脂	頭脳	No	壁紙	頭脳

Yes	新鮮	捕鯨	No	景観	捕鯨
Yes	海図	楽園	No	下駄	楽園
Yes	壁紙	電線	No	骨盤	電線
Yes	監獄	密猟	No	決闘	密猟
Yes	悲鳴	*折鶴	No	補聴	*折鶴
Yes	工場	食塩	No	監獄	食塩
Yes	破裂	変装	No	工場	変装
Yes	砂嵐	断崖	No	樹脂	断崖
Yes	乗客	合宿	No	新鮮	合宿
Yes	進展	質屋	No	乗客	質屋
Yes	角度	売店	No	進展	売店
Yes	下駄	実験	No	砂嵐	実験
Yes	骨盤	連盟	No	洗剤	連盟
Yes	補聴	就職	No	卓越	就職
Yes	木造	交通	No	破裂	交通
Yes	洗剤	短剣	No	宅配	短剣
Yes	宅配	発酵	No	悲鳴	発酵
Yes	景観	両親	No	物価	両親
Yes	卓越	隆起	No	木造	隆起

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