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The effects of visual complexity for Japanese kanji processing with high and low frequencies

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Abstract The present study investigated the effects of visual complexity for kanji processing by selecting target kanji from different stroke ranges of visually simple (2–6 strokes), medium (8–12 strokes), and complex (14–20 strokes) kanji with high and low frequencies. A kanji lexical decision task in Experiment 1 and a kanji naming task in Experiment 2 were administered to native Japanese speakers. Results of both experiments showed that visual complexity inhibited the processing of low-frequency kanji, whereas such consistent, inhibitory effects of visual complexity were not observed in the processing of high-frequency kanji. Kanji with medium complexity were processed faster than simple and complex kanji in high frequency.

Keywords Japanese kanji · Kanji frequency · Strokes · 13th stroke boundary · Visual complexity

Introduction

Unlike English which uses a sequence of simple alphabetic characters, Japanese *kanji* vary in complexity from simple like the kanji 王 (king) to complex like the kanji 題 (title). The visual complexity of kanji seems to affect speed and accuracy of their processing. However, the facilitation/inhibition direction of effects regarding visual complexity on cognitive processing of kanji is not clear. For many years of kanji experiments, visual complexity has been treated as one characteristic of kanji which ought to be controlled prior to running experiments without knowing its

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actual effects (e.g., Hino & Lupker, 1998; Hino, Lupker, Ogawa, & Sears, 2003; Ogawa & Saito, 2006; Tamaoka, 2005, 2007; Tamaoka & Hatsuzuka, 1998; Tamaoka & Taft, 2010). The question, then, remains whether visual complexity facilitates or inhibits kanji processing.

Three assumptions on kanji visual complexity

Visual complexity is fundamentally understood as the bottom-up processing from simple visual features to a single kanji, further to a two-kanji compound, and finally to access the meanings of kanji or compounds (e.g., Taft, 1991; Taft & Zhu, 1997; Tamaoka & Hatsuzuka, 1998). There are three possible assumptions on the effects of visual complexity.

The first assumption is that visual complexity facilitates kanji processing. An early kanji study by Kawai (1966) measured kanji visual complexity by counting lines and points. For instance, a kanji 二 (two) is counted as 2, consisting of two lines, while a kanji 人 (human) is counted as 3 having two lines and one crossing point. Using this measuring approach, Kawai found a high correlation of $r = .76$ ($n = 50$, $p < .001$) between kanji printed-frequency (hear after, kanji frequency) and visual complexity among 50 kanji randomly selected from a list of 1,965. The same 50 kanji, however, showed an even higher correlation of $r = .93$ ($n = 50$, $p < .001$) between kanji frequency and traditional stroke numbers (the way in which kanji are drawn by a Japanese traditional writing brush). Despite Kawai's efforts, stroke count had a stronger correlation with kanji frequency than the line-and-point measure. Furthermore, Kawai tested accuracy of kanji pronunciations among 80 mature native Japanese speakers, and found that the more complex kanji were read more accurately than the less complex ones when kanji frequency is held constant. Consequently, Kawai (1966) concluded that visual complexity facilitated kanji processing from orthography to phonology.

The second assumption is that the difficulty of kanji processing increases up to a certain point of visual complexity while it decreases after the critical point. As depicted in Fig. 1, the token frequency of kanji in the former list of 1,945 commonly-used kanji (Cabinet Announcement by the Japanese Government, 1981) increases with stroke count up to 12 strokes. At 13 strokes, however, the number gradually decreases until the maximum 23 strokes. Taking both visual complexity measured by kanji strokes and the number of existing kanji into consideration, Kaiho (1979) put forward his assumption that difficulty in kanji processing increases proportionally up to 12 strokes, but after the 13th stroke, the number of strokes facilitates kanji processing. In this assumption, Kaiho (1979) disagreed with Kawai (1966) in the way that the difficulty of kanji processing increases up to the 13th stroke, but Kaiho agreed with Kawai's finding that stroke-count facilitate kanji processing after the 13th stroke. Despite the conflicting argument, this assumption of a 13 stroke boundary has not been supported by clear experimental evidence.

The third assumption is that visual complexity inhibits processing of kanji compounds when they are low frequency. Tamaoka and Takahashi (1999) investigated latencies for kanji writing initiation using visually complex/simple

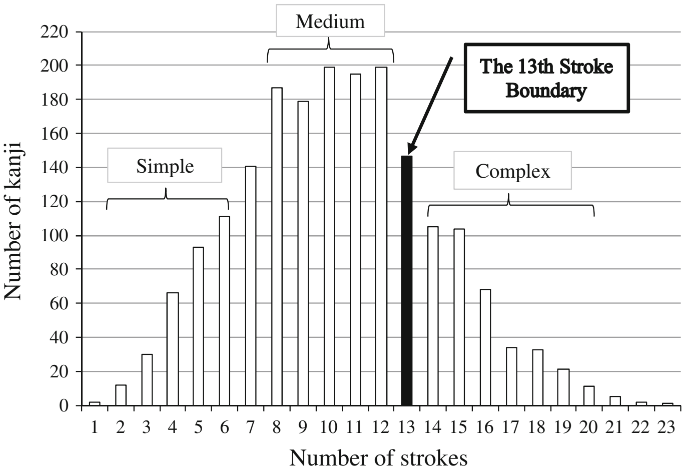

Fig. 1 Stroke distribution of the 1,945 commonly-used Japanese kanji

two-kanji compound words with high and low frequencies. Initiation times for writing behavior indicated kanji visual complexity (number of strokes) inhibited retrieving orthographic representations of two kanji from the mental lexicon when stimuli were low frequency. This tendency was not observed in high frequency kanji. Likewise, Leong, Cheng, and Mulcahy (1987) found that three major factors of simple/complex orthography, high/low printed frequency, and skilled/less skilled reading ability influence the processing of Chinese characters. Although Leong et al. (1987) used Chinese characters, those with less visual complexity (i.e., simple orthography) were processed faster than those with greater visual complexity (i.e., complex orthography) regardless of printed-frequency and skilled/less skilled reading ability. Complex characters with low frequency by less skilled readers were especially slow in processing. As such, Leong et al. (1987) found inhibitory effects of visual complexity on Chinese characters with high frequency as well as with low frequency.

It is well-depicted by various studies (e.g., Hino & Lupker, 1998; Tamaoka & Hatsuzuka, 1995 for Japanese kanji, and Taft, Huang & Zhu, 1994; Taft & Zhu, 1995; Wu, Chou, & Liu, 1994; Zhou & Marslen-Wilson, 1994 for Chinese characters) that kanji frequency per se strongly affects kanji processing. However, neither the first assumption of facilitation effects (Kawai, 1966) nor the second assumption of the 13th stroke boundary (Kaiho, 1979) took word frequency into consideration. Therefore, the present study set high and low word frequencies up as an experimental condition to investigate the effects of visual complexity on Japanese kanji processing.

The sense-determinative and sense-discriminative functions for kanji processing

The theoretical framework for the effects of visual complexity was put forward for interpreting the processing of the Chinese characters from the linguistic perspective by Wang (1973, 1981) and from the psycholinguistic perspective by Leong (1986).

They explicated scriptural double functions of Chinese characters as sense-determinative and sense-discriminative functions. The sense-determinative function works within a single character, which enables a reader to identify its shape by visual features. Putting this function into psycholinguistic terms, visual features of the target character are decoded to activate its orthographic representation which further activates its conceptual and/or phonological representation. In contrast, the sense-discriminative function works among multiple characters, distinguishing the target character from others with similar components.

The first assumption of facilitation effects will be supported when only the sense-determinative function works in all stroke ranges. The more kanji become visually complex, the easier kanji are processed. In contrast, if both sense-determinative and sense-discriminative functions work supplementarily, the second assumption of the 13th stroke boundary (Kaiho, 1979) can be explained as follows. Up to 12 strokes, the sense-discriminative function will help to distinguish the target kanji from others with similar visual complexity while the sense-determinative function will assist to identify the target kanji as visual complexity increases. After the 13th stroke, the number of kanji decreases and visual complexity gets greater. The assumption of the 13th stroke boundary suggests that kanji in the range of 1 to 12 strokes gradually become difficult to identify due to the steady-increase of the number of kanji up to the 12th stroke, but it become easier after the 13th stroke since the number of kanji steadily decreases and since kanji with visual complexity will support the sense-determinative function to work well. Despite the fact that both the first and the second assumptions expect facilitation effects, the third assumption of inhibitory effects depicts quite a different picture. The sense-determinative function does not help speed up kanji processing, but rather slows it down. This inhibitory tendency could be caused by the increase of decoding burden for visual features. The sense-discriminative function, on the other hand, may assist processing kanji in a certain stroke range where various kanji exist.

The 1,945 commonly-used kanji shown in Fig. 1 are normally distributed, having an average of 10.84 strokes with a 3.76 standard deviation (Tamaoka, Kirsner, Yanase, Miyaoka, & Kawakami, 2002). Considering stroke count as an index of visual complexity, utilizing two tasks of kanji lexical decision in Experiment 1 and kanji naming in Experiment 2, the present study investigated the effects of visual complexity on kanji processing by selecting target kanji from three different stroke ranges of visually simple (2–6 strokes), medium (8–12 strokes) and complex (14–20 strokes). Since kanji frequency seems to affect their processing (e.g., Hino & Lupker, 1998; Taft et al., 1994; Taft & Zhu, 1995; Tamaoka & Hatsuzuka, 1995; Wu et al., 1994; Zhou & Marslen-Wilson, 1994), the present study added kanji with high and low frequencies as an experimental condition.

Experiment 1: Kanji lexical decision task

Experiment 1 investigated the effects of visual complexity on kanji processing using a kanji lexical decision task which asked native Japanese speakers to judge whether or not a presented kanji exists in Japanese.

Participants

Participants in Experiment 1 comprised 42 undergraduate and graduate students (22 females and 20 males) at Nagoya University in Japan, all native speakers of Japanese. Ages ranged from 18 years and 7 months to 38 years and 9 months. The average age was 21 years and 1 month with a standard deviation of 3 years and 8 months on the respective day of testing.

Kanji stimuli

As target stimuli, 24 kanji consisting of 12 high and 12 low printed-frequencies were selected from each of three kanji stroke ranges of 2–6, 8–12, and 14–20 (72 kanji in total) out of the 1,945 commonly-used basic kanji taught from the first to the ninth grades of formal schooling to assure that all the participants would be acquainted with them. A lexical decision task (determining whether or not a kanji is correct by pressing a 'Yes' or a 'No' key) was administered using these 72 target kanji for correct 'Yes' responses with another 72 pseudo-kanji for correct 'No' responses. All stimuli are listed in "Appendix 1" for real kanji and "Appendix 2" for pseudo-kanji.

As shown in Table 1, eight different features controlled 72 target kanji. The experimental condition of visual complexity as measured by the number of kanji strokes (#1 in Table 1) was controlled by selecting kanji from the three different specific ranges. This feature showed a significant main effect of three visual complexity groups of simple, medium, and complex [$F(2, 69) = 368.907$, $p < .001$]. Another experimental condition of high and low kanji frequency was manipulated by three different indexes (#2–4). First, *Kokuritsu Kokugo Kenkyujyo* (National Institute for Japanese Language and Linguistics) in 1976 calculated kanji frequencies of appearance for 1,000 kanji (#2) from three major newspapers, *Asashi*, *Yomiuri*, and *Mainichi*, during the year 1966, showing a significant difference between two groups of high and low kanji frequencies [$t^{L}(35.683) = 8.926$, $p < .001$[1]]. Second, Yokoyama, Sasahara, Nozaki, and Long (1998) published kanji frequency data based on all the kanji in the Tokyo edition of the *Asahi* newspaper printed in 1993 (#3), again showing a significant difference between high and low kanji frequency groups [$t^{L}(36.009) = 8.771$, $p < .001$]. Third, CD-ROM versions of the Tokyo edition of the *Asahi* newspaper in 1993 (#4) also showed a significant difference between high and low kanji frequency groups [$t^{L}(36.009) = 8.357$, $p < .001$]. Three different kanji frequency indexes showed a great difference in the experimental condition of kanji frequency.

There were four control conditions (#5–#8). The school grade in which the target kanji are taught was also taken into consideration. The assignment of the first 1,006 basic kanji to each school grade follows the Japanese language curriculum as outlined by the Japanese Ministry of Education in 1989. Since the remaining

[1] Levene's test rejected a homogeneous variance assumption in two kanji high and low frequency groups, so that a *t* test with no assumption of homogeneity of variance was used to analyze the data. This *t* test is marked by ^{L} and hereafter the same.

Table 1 Features of kanji with visual complexity of *simple*, *medium*, and *complex*

#	Kanji features	Simple ($n = 24$)		Medium ($n = 24$)		Complex ($n = 24$)	
		M	SD	*M*	SD	*M*	SD
1	Number of strokes	4.79	1.06	9.67	1.31	15.71	1.73
2	Kanji frequency in 1976	0.45	0.69	0.73	0.87	0.60	0.77
3	Kanji frequency in 1993	6,421	11,201	14,890	16,749	11,558	15,883
4	Kanji frequency in CD 1993	10,140	18,180	21,937	25,978	15,916	21,849
5	School grades	5.08	2.10	5.46	1.72	5.58	1.67
6	JLPT-test	1.63	0.71	1.61	0.72	1.64	0.66
7	Number of homophones	17.92	17.00	16.17	15.25	11.04	8.13
8	Radical frequency	25.75	30.29	40.83	34.38	43.25	32.39

M means, *SD* standard deviations

939 basic kanji are taught in Grades 7–9; these are all recorded with the numeral '7'. Using these figures, the averages of school grades were calculated (#5). Visual complexity did not show a main effect [$F(2, 69) = 0.480$, $p = .621$, *ns*]. Thus, the three visual complexity groups of target kanji have no differences among the grades in which they are taught at school. In contrast, the difference between the high and low kanji frequency groups showed a significant difference [$t^{L}(64.598) = 8.870$, $p < .001$], indicating that high frequency kanji were taught at higher grades than were low frequency kanji. Kanji assignment to the four levels of the former version of the Japanese Language Proficiency Test (#6) was used to control three visual complexity conditions, with no main effect apparent [$F(2, 69) = 0.009$, $p = .991$, *ns*], but showing a significant difference between high and low frequency [$t^{L}(52.900) = 9.410$, $p < .001$]. The number of kanji On- and Kun-reading homophones (#7) was counted according to how many kanji out of the 1,945 basic kanji shared the same sound (Tamaoka, Kirsner, Yanase, Miyaoka, & Kawakami, 2002). There was no significant main effect of visual complexity [$F(2, 69) = 1.564$, $p = .217$, *ns*], and no significant difference between high and low frequency [$t(70) = 0.058$, $p = .954$, *ns*.]. Radical frequency (#8) counted how many of the 1,945 basic kanji share the same radical (Tamaoka, et al., 2002). Again, no significant main effect of visual complexity was found [$F(2, 69) = 2.057$, $p = .136$, *ns*], and there was no significant difference between high and low frequency [$t(70) = 1.011$, $p = .315$, *ns*.]. Overall, visual complexity was well-controlled in these four kanji features. However, kanji frequency was associated with the other features of school grade and the Japanese language proficiency (JLP) test level. Basically, high frequency kanji were allocated at the earlier school grades and the easier level of the JLP test.

Procedure

All real and pseudo kanji were randomly presented one-by-one to participants in the center of a computer screen 600 ms after the appearance of an eye fixation point marked by '*'. Stimulus randomization was operated with each participant, so that each was presented with a different order of stimulus items. The participants were instructed to respond as quickly and as accurately as possible in deciding whether or not the kanji exists in Japanese, by pressing the 'Yes' or 'No' response key. After the response, the participant pressed the space key to initiate the next presentation. With an interval of 600 ms, the eye fixation point '*' appeared for 600 ms, after which a new kanji stimulus was shown to the participant. Participants repeated this process until all the real kanji and pseudo kanji were presented in the font of MS Gothic. Each response (i.e., reaction) time and its result of correct or incorrect were automatically recorded by computer. Sixteen practice trials were given to participants before the commencement of actual testing.

Analysis and results

Prior to the analysis of reaction times for both correct 'Yes' and 'No' responses, extremes among kanji lexical decision times (responses slower than 300 ms or longer than 3,000 ms) were recorded as missing values. Responses outside of 2.5 standard deviations at both high and low ranges were replaced by boundaries indicated by 2.5 standard deviations from the individual means of participants in each category. Only correct 'Yes' and 'No' responses were used for the analysis of reaction times.

The means of correct 'Yes' reaction times and error rates for kanji lexical decisions are reported in Table 2. The data were analyzed using a linear mixed effects (LME) methodology (Baayen, 2008; Baayen, Davidson, & Bates, 2008). A two-way 3 (visual complexity; simple, medium, or complex) × 2 (kanji frequency; high or low) ANOVA was conducted on reaction times. The main effects of visual complexity [$F(2, 141.261) = 31.546$, $p < .001$] and kanji frequency [$F(1, 1{,}368.486) = 307.566$, $p < .001$] were significant. Their interaction [$F(2, 3{,}065.211) = 60.381$, $p < .001$] was also significant.

Further analyses were conducted on high and low kanji frequency separately. For kanji with high frequency, a LME one-way ANOVA for visual complexity showed a significant main effect [$F(2, 1{,}578.199) = 6.324$, $p < .01$]. Multiple comparisons by the LSD method showed the significances of medium ($M = 482$ ms) < simple

Table 2 Reaction times and error rates for kanji lexical decision of correct items

Kanji frequency	Visual complexity	Reaction time (ms)		Error rate (%)	
		M	SD	*M*	SD
High	Simple	493	89	2.72	16.27
	Medium	482	80	1.45	11.96
	Complex	498	94	1.27	11.20
Low	Simple	502	81	2.17	14.60
	Medium	564	115	9.96	29.98
	Complex	582	126	12.68	33.31

$n = 42$

M means, *SD* standard deviations

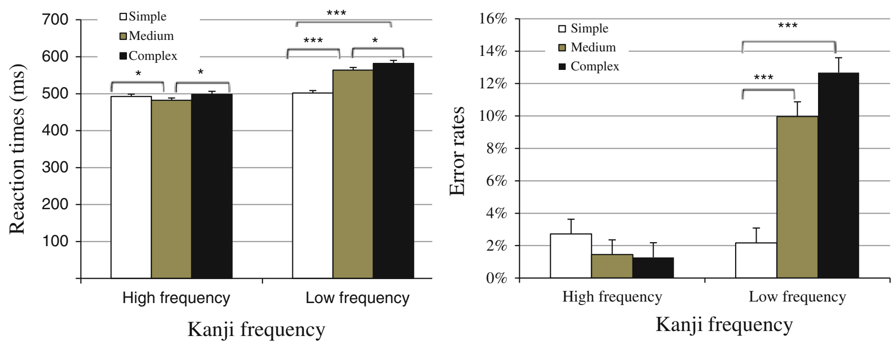

Fig. 2 Lexical decision for correct kanji (correct 'Yes' responses) in function of high/low kanji frequencies and visual complexity. * $p < .05$. ** $p < .01$. *** $p < .001$. Bars indicate SE

($M = 493$ ms) = complex ($M = 498$ ms). Likewise, the same one-way ANOVA for kanji with low frequency also showed the significant main effect [$F(2, 2{,}235.100) = 58.945$, $p < .001$]. Multiple comparisons by the LSD method indicated simple (M = 502 ms) < medium ($M = 564$ ms) < complex ($M = 582$ ms)]. Results of reaction times are depicted in Fig. 2.

Likewise, the same LME two-way ANOVA was conducted on error rates. Main effects of visual complexity [$F(2, 3{,}306.000) = 13.128$, $p < .001$] and frequency [$F(1, 3{,}306.000) = 75.300$, $p < .001$], and their interaction [$F(2, 3{,}306.000) = 23.388$, $p < .001$] were all significant. Further analyses were conducted on high and low kanji frequency separately. For kanji with high frequency, a LME one-way ANOVA for visual complexity showed no significant main effect [$F(2, 1{,}653.113) = 1.936$, $p = .145$, *ns*.]. The same multiple comparisons by the LSD method naturally showed no significant difference among complex (M = 1.27 %), medium (M = 1.45 %) and simple (M = 2.72 %) in high frequency. For kanji with low frequency, the same LME one-way ANOVA for visual complexity showed a significant main effect [$F(2, 3{,}031.121) = 3.627$, $p < .05$]. Again, the same multiple comparisons by the LSD method were conducted to three groups of visual complexity, indicating simple (M = 2.17 %) < medium (M = 9.96 %) = complex (M = 12.68 %). The results of error rates are depicted in Fig. 2.

The means of reaction times and error rates for correct 'No' responses of kanji lexical decision are reported in Table 3. Only correct responses were used for the analysis of reaction times. The main effect of visual complexity on reaction times analyzed by a LME one-way ANOVA was significant [$F(2, 3{,}031.121) = 3.627$, $p < .05$]. The LSD Multiple comparisons indicated significances of medium (M = 544 ms) < simple (M = 557 ms), but complex (M = 550 ms) fell between them. However, error rates did not show a significant main effect of visual complexity [$F(2, 429.080) = 2.258$, $p = .106$, *ns*.].

Discussion

The results of kanji lexical decision in Experiment 1 indicated that the effects of visual complexity changes depending on high/low kanji frequency. Kanji with low

Table 3 Reaction times and error rates for kanji lexical decision for incorrect items

Visual complexity	Reaction time (ms)		Error rate (%)	
	M	SD	*M*	SD
Simple	557	108	0.08	0.27
Medium	544	108	0.06	0.23
Complex	550	125	0.08	0.27

$n = 42$

M means, *SD* standard deviations

frequency showed a clear inhibitory trend from simple to complex in both reaction times and error rates. Thus, Experiment 1 did not support the first assumption of facilitation effects (Kawai, 1966). On the other hand, kanji with high frequency showed a different trend. For the reaction time data, kanji with the medium range from 8 to 12 strokes were faster to process than those with the simple and complex stroke ranges. In contrast, the error rate data for kanji with low frequency showed a flat trend from simple to complex. Despite the second assumption of inhibitory effects in the medium range (Kaiho, 1979), the reversal prediction of facilitation effects was observed in Experiment 1. The third assumption of inhibitory effects proposed by Tamaoka and Takahashi (1999) and Leong et al. (1987) was supported by reaction times and error rates of kanji with low frequency. However, as observed by initiation latency times for writing behavior (Tamaoka & Takahashi, 1999), kanji with high frequency showed a different trend from those with low frequency; kanji in the medium range complexity were more quickly processed than simple and complex ones.

Experiment 2: Kanji naming task

Experiment 2 investigated the effects of visual complexity on kanji processing using a kanji naming task asking native Japanese speakers to pronounce kanji presented to them.

Participants

Participants in Experiment 2 comprised 40 undergraduate and graduate students (21 females and 19 males) at Nagoya University in Japan, all native speakers of Japanese. Ages ranged from 18 years and 4 months to 34 years and 6 months. The average age was 20 years and 11 months with a standard deviation of 3 years and 4 months on the respective day of testing.

Kanji stimuli

Since pseudo kanji cannot be pronounced, Experiment 2 used only the real kanji (kanji items for correct ‘Yes’ responses) in Experiment 1.

Procedure

Real kanji were randomly presented to participants in the center of a computer screen 600 ms after the appearance of an eye fixation point marked by '*'. Stimulus randomization was operated with each participant, so that each was presented with a different order of stimulus items. Participants were instructed to pronounce the kanji presented to them as quickly and as accurately as possible. After the response, an experimenter pressed the space key to initiate the next presentation. With an interval of 600 ms, the eye fixation point '*' appeared for 600 ms, after which a new kanji stimulus was shown to the participant. Participants repeated this process until all the real kanji were presented. The naming latency of each kanji pronunciation was recorded by computer, with correct or incorrect response results input by the experimenter. Ten practice trials were given to participants before the commencement of actual testing.

Analysis and results

Prior to the analysis of reaction times, extremes among kanji naming times (responses slower than 300 ms or longer than 3,000 ms) were recorded as missing values. Responses outside of 2.5 standard deviations at both high and low ranges were replaced by boundaries indicated by 2.5 standard deviations from the individual means of participants in each category. The means of correct naming latencies and error rates was reported in Table 4. Only correct responses were used for the analysis of reaction times.

The data were analyzed using a linear mixed effects methodology. A two-way, 3 (visual complexity; simple, medium, or complex) × 2 (kanji frequency; high or low) ANOVA was conducted on naming latencies for kanji naming. Both the main effects of visual complexity [$F(2, 318.527) = 7.633$, $p < .001$] and frequency [$F(1, 1{,}988.158) = 204.905$, $p < .001$] were significant. Their interaction [$F(2, 2{,}488.992) = 18.987$, $p < .001$] was also significant.

Further analyses were conducted on high and low kanji frequency separately. For kanji with high frequency, a LME one-way ANOVA for visual complexity showed

Table 4 Naming latencies and error rates for *simple*, *medium*, and *complex* kanji

Kanji frequency	Visual complexity	Naming latency (ms)		Error rate (%)	
		M	SD	*M*	SD
High	Simple	602	166	0.00	0.00
	Medium	572	127	0.00	0.00
	Complex	603	199	0.23	4.76
Low	Simple	648	255	0.68	8.24
	Medium	722	276	1.00	9.97
	Complex	736	274	0.82	9.00

$n = 42$

M means, *SD* standard deviations

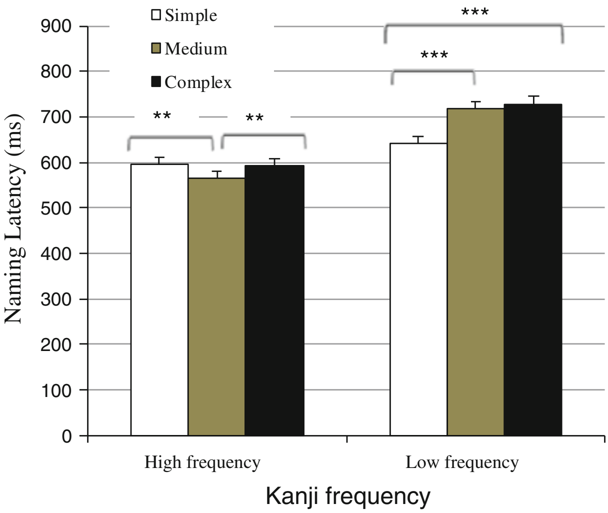

Fig. 3 Naming latencies for kanji in function of high/low kanji frequencies and visual complexity. * $p < .05$. ** $p < .01$. *** $p < .001$. Bars indicate SE

a significant main effect [$F(2, 316.833) = 7.453$, $p < .001$]. Multiple comparisons by the LSD method showed the significances of medium ($M = 572$ ms) < simple ($M = 602$ ms) = complex ($M = 603$ ms) in high frequency. For kanji with low frequency, a LME one-way ANOVA for visual complexity showed the significant main effect [$F(2, 1{,}157.797) = 19.829$, $p < .001$]. Multiple comparisons by the LSD method showed that simple ($M = 648$ ms) < medium ($M = 722$ ms) = complex ($M = 736$ ms) in low frequency. The results are depicted in Fig. 3.

The same ANOVA was conducted on error rates. The main effect of visual complexity [$F(2, 2{,}723.380) = 0.072$, $p = .931$, *ns*.] was not significant while the main effect of frequency [$F(1, 2{,}576.575) = 7.847$, $p < .01$] was. However, their interaction was not significant [$F(2, 2{,}539.696) = 0.237$, $p = .789$, *ns*]. Thus, the results simply indicate that high frequency kanji were named more accurately than were low frequency ones.

Discussion

The results of kanji naming in Experiment 2 indicated a similar trend as observed in Experiment 1, suggesting that the effects of visual complexity change depending on kanji frequency. Kanji with low frequency showed a clear inhibitory trend from simple to complex in naming latencies, but not in error rates. However, for high frequency, kanji in the medium stroke range were faster to process for naming than those in the simple and complex stroke ranges. Despite the prediction of inhibition by Kaiho (1979), kanji in the medium range of 8–12 strokes showed the reversal result of facilitation. Neither the first assumption nor the second assumption was supported by the results of Experiment 2, which fits to the third assumption of inhibitory effects depending on kanji frequency (Tamaoka & Takahashi, 1999).

General discussion

Without clarifying the effects of visual complexity, it is usually treated as one characteristic of kanji which ought to be controlled prior to running experiments (e.g., Hino & Lupker, 1998; Hino et al., 2003; Ogawa & Saito, 2006; Tamaoka, 2005, 2007; Tamaoka & Hatsuzuka, 1998; Tamaoka & Taft, 2010). The present study, therefore, conducted two experiments of kanji lexical decision in Experiment 1 and kanji naming in Experiment 2 on the kanji processing in function of simple/medium/complex visual complexity and high/low frequency. As suggested by previous studies (e.g., Hino & Lupker, 1998; Tamaoka & Hatsuzuka, 1995 for Japanese kanji, and and Taft et al., 1994; Taft & Zhu, 1995; Wu et al., 1994; Zhou & Marslen-Wilson, 1994 for Chinese characters), kanji frequency played a major function for kanji processing. Similar to the findings of Tamaoka and Takahashi (1999) on the initiation times for kanji writing behavior, the results of both experiments in the present study supported the third assumption of visual complexity effects depending on kanji frequency.

Results of the present study related to the three assumptions

A clear incline was observed among kanji with low frequency. Visual complexity affected speed and accuracy of kanji processing in the inhibitory direction; the heavier its complexity becomes, the slower kanji is processed. The sense-determinative function seems not to work well among kanji with low frequency; rather, the present result among low frequency kanji is simply explained by the idea that decoding from complex features takes longer than simpler ones. This clear inhibitory trend from simple to complex was supported by the study on Chinese characters by Leong et al. (1987) as well as Japanese kanji by Tamaoka and Takahashi (1999). Thus, the results of the present study rejected the first assumption of the linear facilitation trend of visual complexity proposed by Kawai (1966).

Kanji with high frequency showed that kanji in the medium complexity of the 8–12 stroke range were more quickly processed than those in the simple 2–6 and the complex 14–20 stroke-range complexity. The 13th stroke boundary of the second assumption (Kaiho, 1979) predicted the kanji in the medium stroke range to be difficult to process due to the need to distinguish the target kanji from many other kanji in the same stroke range, but after the 13th stroke, kanji processing becomes easier with the help of the sense-determinative function generated by visually-complex kanji features. However, despite this expectation, the present study among kanji with high frequency indicated a different pattern: that is, kanji in the medium range were processed faster than kanji in the simple range of below 6 strokes and kanji in the complex range of over 14 strokes, but the ranges of simple and complex did not differ from one another. Indeed, the 13th stroke boundary showed a clear difference in processing of kanji with high frequency, but its trends of processing speed indicated the opposite direction. As such, the results of the experiments refuted the assumption of the 13th stroke boundary put forward by Kaiho (1979).

It is rather unanticipated that kanji of the medium stroke range with high frequency were processed more quickly than the simple and the complex items with high frequency. The question rose what caused the discrepancy in the findings with high-frequency kanji between the medium, and the simple/complex items. The present study found no difference for kanji lexical decision and naming between the simple and complex kanji in high frequency. Instead of an explanation using the functions of sense-discrimination and sense-determination (Leong, 1986; Wang, 1973, 1981), the straight-forward and simple explanation for this trend is that frequently-used kanji are processed holistically as a whole single unit, which eliminates the influence of kanji visual complexity. In contrast, kanji with low frequency required bottom-up processing from small figures to kanji via constructing units, resulting in inhibitory effects depending on visual complexity. Yet, the question still remains why kanji with the medium 8–12 stroke range were processed faster than simple and complex kanji in high frequency.

Explanation for the facilitation effects on processing of kanji in the 8—12 medium range strokes

Although the results in the present study did not support Kaiho's original 13th stroke boundary, a distinct difference in kanji processing seems to be created around this boundary. One of potential characteristics of kanji visual complexity in the medium range influencing kanji processing could be a smaller unit which constructs a whole kanji. Visual units of radicals are used for classifying kanji in a kanji dictionary. In fact, radicals produce various kanji especially in the medium 8–12 stroke range. For example, a frequently-used radical 木 (tree) constructs 8 stroke kanji of 板 (board), 杯 (cup) and 林 (grove), 9 stoke kanji of 柱 (post), 枯 (blight) and 柿 (persimmon), 10 stroke kanji of 桜 (cherry blossom), 株 (stock), and 桃 (peach), 11 stroke kanji of 梓 (Japanese cherry birch), 梢 (treetop), and 梗 (hard branch), and 12 stroke kanji of 検 (examine), 棟 (ridge) and 棒 (bar). In the present study, both Experiments 1 and 2 indicated that kanji in the medium stroke range facilitated processing.

Regarding kanji radicals, two possible frequencies may be related to kanji processing. First, the *radical (token) frequency* indicates how often each radical occurs in written materials. Second, *radical neighborhood size* refers to how frequently a specific radical constructs kanji. If kanji in the medium stroke range are likely to be characterized as those with high radical frequency and high neighborhood size, it should be assumed that high radical frequency and high radical neighborhood size should facilitate kanji processing according to the results of the present study. Two studies on Chinese characters (Feldman & Siok, 1997; Taft & Zhu, 1997), not Japanese kanji, indicated Chinese characters with lower radical neighborhood size showed higher error rates and slower processing speed than those with higher radical neighborhood size. Taft and Zhu (1997) explained that in the case of high radical neighborhood size, a specific radical constructing a target character received higher activations from multiple characters embedded in the same radical, which strengthens the connection with the target character and results in the facilitation effects. Although the experiments by Feldman and Siok (1997) and Taft and Zhu (1997) were conducted on Chinese characters, they can provide an explanation; high-frequency kanji in the medium stroke range are likely to have higher radical neighborhood size, which produces the facilitation effects for kanji processing.

Masuda and Saito (1999), conducting experiments on Japanese kanji, reported the reversal direction of inhibitory effects regarding kanji radical frequencies and their neighborhood size. They conducted two experiments using side-by-side kanji (e.g., 日 + 寺 = 時, and likewise, 討, 秩, 牧, 特 etc.). In Experiment 1, after presenting two kanji (e.g., 研 and 秒) within 40 ms, participants were asked to write these radicals and then whole kanji. The result indicated that kanji with high radical frequency were more accurately written than those with low radical frequency. Furthermore, another experiment under the same experimental condition as the first was conducted by manipulating radical neighborhood size controlling frequencies of radicals (all of which appear in the left side of the kanji) and kanji. The results showed that kanji with low neighborhood size were more accurately written than kanji with high neighborhood size. They explain that kanji with larger neighborhood size will activate multiple kanji sharing the same radical. Native Japanese speakers have to suppress these kanji to identify the target kanji which creates the inhibitory effects for kanji processing. As such, both facilitation and inhibition were observed in processing the logographic script of Chinese characters and Japanese kanji regarding radical neighborhood size.

Conclusion

The present study suggests that the effects of kanji visual complexity changes depending on kanji frequency. In low frequency, visual complexity shows inhibitory effects throughout the whole kanji stroke range: The more visually complex kanji become, the longer processing times are required. In high frequency, kanji could be processed holistically, which removes visual inhibitory effects. However, kanji in the medium complexity 8–12 stroke range seem to have additional factors which facilitate processing speed of these kanji. A possible candidate will be radical frequency and radical neighborhood size. However, previous studies provide both predictions of facilitation (Feldman & Siok, 1997; Taft & Zhu, 1997) and inhibition (Masuda & Saito, 1999). Consequently, the reason why kanji in the medium 8–12 stroke range were processed faster than simple and complex kanji in high frequency still remains as an unanswered question.

Appendix 1

See Table 5.

Table 5 Target kanji list for correct 'Yes' responses

Target kanji	Strokes	Kanji frequency in 1976	Kanji frequency in 1993	Kanji frequency in CD 1993	School grades	JLPT-test level	Number of homophones	Radical frequency
High frequency kanji								
2–6 stroke range of simple kanji								
士	3	0.833	12,812	18,686	4	1	45	5
王	4	0.500	5,126	6,900	1	2	12	11
区	4	2.529	28,396	47,382	3	2	4	4
刊	5	0.251	3,482	5,235	5	2	44	30
令	5	0.336	3,546	5,196	4	2	12	99
巨	5	0.279	3,730	4,875	7	2	9	2
央	5	0.553	6,193	9,028	3	2	12	15
号	5	0.694	6,374	10,745	3	2	5	59
刑	6	0.218	3,796	6,081	7	1	26	30
宅	6	0.693	10,205	16,699	6	2	7	35
件	6	0.896	18,778	29,821	5	2	29	99
百	6	2.465	47,834	77,092	1	4	1	5
8–12 stroke range of medium kanji								
官	8	1.116	23,006	27,898	4	2	44	35
協	8	1.204	29,389	40,125	4	2	26	11
制	8	1.268	38,664	49,142	5	2	31	30
信	9	1.259	22,480	30,898	4	2	28	99
派	9	0.876	22,524	29,087	6	1	5	109
界	9	1.411	25,873	33,592	3	3	21	17
県	9	1.281	29,515	67,055	3	2	29	15
約	9	1.634	37,694	63,182	4	2	5	61
院	10	1.083	24,304	33,743	3	3	10	28
員	10	3.133	57,256	88,150	3	3	10	59
第	11	2.404	23,490	34,077	3	2	5	22
14–20 stroke range of complex kanji								
税	12	0.672	22,145	27,932	5	2	1	22
算	14	0.761	12,811	18,190	2	2	12	22
銀	14	0.982	13,738	20,006	3	3	2	29
演	14	1.159	16,895	21,805	5	2	14	109
領	14	0.747	20,686	24,221	5	2	13	17
総	14	1.529	30,736	41,544	5	2	33	61
談	15	0.829	13,397	17,917	3	2	8	61
億	15	0.663	18,874	29,211	4	2	3	99
論	15	0.965	19,537	25,340	6	2	1	61
輸	16	0.618	13,682	19,522	5	2	6	15
職	18	0.761	15,835	26,932	5	2	9	5
題	18	2.039	32,315	41,310	3	3	5	17
議	20	3.049	67,809	94,398	4	2	11	61

Table 5 continued

Target kanji	Strokes	Kanji frequency in 1976	Kanji frequency in 1993	Kanji frequency in CD 1993	School grades	JLPT-test level	Number of homophones	Radical frequency
Low frequency kanji								
2–6 stroke range of simple kanji								
寸	3	0.041	363	539	6	1	1	12
才	3	0.356	644	837	2	2	21	79
厄	4	0.000	67	98	7	1	5	4
孔	4	0.019	102	151	7	1	60	9
冗	4	0.020	212	292	7	1	20	3
尺	4	0.013	219	292	6	1	6	14
凶	4	0.021	499	743	7	1	26	4
皿	5	0.029	486	692	3	2	0	8
芋	6	0.000	47	67	7	1	0	36
迅	6	0.000	132	177	7	1	8	49
壮	6	0.053	417	600	7	1	33	5
缶	6	0.028	654	1,138	7	2	44	1
8–12 stroke range of medium kanji								
奔	8	0.012	156	215	7	1	3	15
侯	9	0.000	66	84	7	–	60	99
姻	9	0.000	91	119	7	1	10	32
幽	9	0.012	95	146	7	1	14	4
峠	9	0.020	107	208	7	1	0	13
倹	10	0.000	36	51	7	1	29	99
蚊	10	0.018	81	112	7	1	0	7
殉	10	0.010	81	131	7	1	11	5
栓	10	0.000	81	140	7	1	26	75
惰	12	0.000	46	68	7	1	5	70
蛮	12	0.010	74	112	7	1	4	7
塀	12	0.000	114	215	7	1	11	46
14–20 stroke range of complex kanji								
寡	14	0.000	84	102	7	1	31	35
嫡	14	0.000	98	125	7	1	2	32
概	14	0.071	230	327	7	1	8	75
遵	15	0.000	6	7	7	1	11	49
墾	16	0.000	21	36	7	1	11	46
儒	16	0.000	48	65	7	1	6	99
嬢	16	0.034	108	151	7	1	20	32
錠	16	0.291	125	303	7	1	20	29
隷	16	0.000	126	144	7	–	12	1
爵	17	0.000	65	69	7	–	6	1
擬	17	0.012	121	215	7	1	11	79
韻	19	0.000	48	55	7	1	10	3

Appendix 2

See Table 6.

Table 6 Pseudo kanji list for correct 'No' responses

2-6 stroke range (simple)		8-12 stroke range (medium)		14-20 stroke range (complex)	
Pseudo kanji	Strokes	Pseudo kanji	Strokes	Pseudo kanji	Strokes
历	4	斧	8	瓏	14
旭	4	茾	8	褐	14
攴	4	吾	9	僅	14
仅	4	陔	9	蓁	14
加	4	弼	9	違	14
芎	5	匧	9	魃	15
轧	5	条	9	闌	15
因	5	粦	9	豐	15
区	5	戔	10	護	15
廴	5	氰	10	錠	15
宊	5	瘤	10	緩	15
妥	5	奇	10	綢	15
毒	6	匪	10	翼	16
旱	6	走	10	黨	16
匈	6	恵	10	基	16
厗	6	香	10	翯	16
宣	6	基	10	麈	17
㕛	6	胎	11	齡	17
矛	6	虐	11	鄉	17
坻	6	庖	11	壽	18
考	6	柴	11	顯	18
卬	6	漲	11	蓬	19
次	6	䏙	12	箭	19
吼	6	渜	12	雷	20

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Hepburn style romanization with no vowel repeated for a long vowel is used for describing Japanese authors' and publishers' names while the same style with vowel repeated for a long vowel is used for Japanese article titles and journal names

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