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Semantic processing of Arabic, Kanji, and Kana numbers: Evidence from interference in physical and numerical size judgments

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Two experiments were conducted with the following objectives: (1) to replicate the finding of similar semantic representation of Arabic and written-word (Kanji and Kana) numbers with a direct numerical task, (2) to investigate the automatic semantic processing of Arabic and written-word numbers, and (3) to verify whether the assumption of a common semantic representation is valid in an indirect numerical task. Subjects were asked to judge which of two numbers (e.g., 6–8) was larger either in its numerical size (Experiment 1) or in its physical size (Experiment 2) using the three notations. Effects of two factors were analyzed: the congruity between numerical and physical size and the numerical distance. The effects of these factors were very similar across the three notations in Experiment 1, but were drastically different in Experiment 2. The results of Experiment 2 demonstrated the nonsemantic processing of Kana numbers, and suggest that there may be separate semantic representations for Arabic and Kanji numbers.

One of the unique features of numbers is that a meaning (i.e., magnitude information) can be externally represented by several different notations, such as Arabic and written-word numbers (Noel, 2001). Because of this uniqueness, psychologists and neuropsychologists have pondered whether there are functionally independent systems dependent on Arabic (e.g., 6) and written-word numbers (e.g., six). Neuropsychological evidence has indicated that separate brain areas are associated with identification of Arabic and written-word numbers, suggesting that two types of notation are represented separately at the identification level (e.g., Anderson, Damasio, & Damasio, 1990; L. Cohen & Dehaene, 2000; Dehaene, 1995, 1996; Dehaene & Cohen, 1997; Dehaene et al., 1996; Hatta & Tsuji, 1993; Pinel et al., 1999; Stanescu-Cosson et al., 2000).

Despite these differences, cognitive psychological studies have demonstrated that a similar *distance effect* can be observed in both Arabic and written-word numbers (e.g., Dehaene & Akhavein, 1995; Dehaene, Dupoux, & Mehler, 1990). This distance effect refers to the finding that reaction time (RT) decreases as the distance that separates the stimuli increases, and has been considered to reflect semantic representation (e.g., Banks & Flora, 1977; Dehaene, 1989; Jamieson & Petrusic, 1975; Marks, 1972; Moyer & Landauer, 1967). Such data suggest that the two notations are similarly represented at the semantic level. In fact, the findings of recent brain imaging studies have suggested that a common neural substrate might be associated with semantic processing regardless of input notation (Dehaene, 1995; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Dehaene et al., 1996).

Dehaene (1992) proposed a model of number cognition called the *triple code model* (see also Dehaene & Cohen, 1995). This model assumes three types of internal representations for number cognition: *visual number form*, *verbal word frame*, and *analogue magnitude representation.* Both visual number form and verbal word frame are notation-dependent representations, which are representations at the identification level for the visual numbers (e.g., Arabic and written-word numbers) and the spoken numbers, respectively. Further, Dehaene (1998) argued that there are separate visual identification systems for Arabic and written-word numbers. The analogue magnitude representation is a notation-independent semantic representation, and assumed to be a left-to-right, compressed, analogue number line (Dehaene, Bossini, & Giraux, 1993; Dehaene et al., 1990; Reynvoet & Brysbaert, 1999).

According to Dehaene, both Arabic and written-word numbers are automatically translated into a common notation-independent semantic representation, analogue magnitude representation, when people see numbers (Dehaene & Akhavein, 1995). In other words, it is assumed that semantic activation of numbers is mandatory even when the task requirement is irrelevant to semantic information. In the present article, we used the term *indirect numerical task* when the task requirement was irrelevant to semantic information and defined *automatic*

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semantic activation as semantic activation in the indirect numerical task. In contrast, we used the term *direct numerical task* when the task requirement was relevant to semantic information.

The strengths of Dehaene's model are that (1) it is neuroanatomically elaborated, and (2) it has the power to explain various available data (e.g., Banks, Fujii, & Kayra-Stuart, 1976; L. Cohen & Dehaene, 1996; Dehaene et al., 1993; Dehaene & Cohen, 1997; Fias, Brysbaert, Geypens, & d'Ydewalle, 1996).

Lately, however, Dehaene's model has been subjected to criticism. First, automatic semantic activation of written-word numbers is uncertain. Many studies have indicated that Arabic numbers can be processed semantically even in an indirect numerical task (e.g., Dehaene et al., 1993; Dehaene et al., 1990; Fias et al., 1996; Henik & Tzelgov, 1982; Tzelgov, Meyer, & Henik, 1992). However, only a few studies have examined the semantic activation of written-word numbers using an indirect numerical task. For example, Dehaene and Akhavein (1995) found similar symbolic distance effects between Arabic and written-word numbers with the indirect numerical task (same–different judgment of physical appearance) and concluded that the meaning of a number is automatically activated even when the task requirement is irrelevant to semantic information. But Fias (2001) examined the semantic processing of written-word numbers with a different indirect numerical task (phoneme monitoring) and demonstrated the nonsemantic processing of the written-word number (i.e., translation from written-word numbers to phonological code without semantic activation). Because available evidence is limited and the results of the studies are inconsistent, further studies are necessary to conclude whether written-word numbers are automatically translated into semantic representations.

Moreover, and more important, the assumption of "a common semantic representation" is challenged. This problem can apply to another dominant model, that of McCloskey, in which a notation-independent semantic representation is also assumed (McCloskey, Caramazza, & Basili, 1985). Koechlin, Naccache, Block, and Dehaene (1999) commented on this assumption on methodological grounds. They noted that "because of the speed with which humans process information, it can be extremely difficult to prove or disprove issues about the modularity of information processing in the human brain by using data from normal participants" (p. 1892). Nevertheless, the assumption of a common semantic representation is based on findings from studies in which normal subjects performed the direct numerical task (e.g., numerical size judgment). It is plausible that notation-dependent semantic processing could be obscured in the direct numerical task. Thus, the indirect numerical task should be used for addressing the issue of notation-dependent semantic representations.

The aims of present study were (1) to replicate the previous findings with the direct numerical task (i.e., the similar semantic representation between Arabic and written-word numbers), (2) to investigate whether both Arabic and written-word numbers are translated into semantic representations automatically, and (3) to verify whether the assumption of "a common semantic representation" is valid using the indirect numerical task. We addressed the first issue in Experiment 1 and the second and third in Experiment 2.

For these purposes, we extended Experiment 2 of Henik and Tzelgov (1982), in which they asked subjects to judge which of two Arabic numbers was larger either in numerical or physical size (e.g., 2–4 or 2–6). Numerical size judgment can be considered to be a direct numerical task, whereas physical size judgment is an indirect numerical task. They manipulated two critical variables: congruity and numerical distance. The factor of congruity consisted of two levels, congruent and incongruent. In the congruent condition, larger numbers in physical size were also larger in numerical size (e.g., 2–4). In contrast, in the incongruent condition, larger numbers in physical size were smaller in numerical size (e.g., 2–4). The factor of distance also consisted of two levels, "close" and "far." In their study, "close" was defined as two-unit distance pairs (e.g., 2–4), and "large" was defined as four-unit distance pairs (e.g., 2–6). Henik and Tzelgov found that RT was faster in the congruent condition than in the incongruent condition in numerical size judgments. This is called the *congruity effect* (e.g., Besner & Coltheart, 1979; Hatta, 1983; Takahashi & Green, 1983; Tzelgov et al., 1992). RT in the far condition was faster than in the close condition in numerical size judgments (i.e., symbolic distance effect, see Moyer & Landauer, 1967), and the congruity effect was also found in physical size judgments. Furthermore, in the physical size judgments, an interaction between congruity and numerical distance was also found. In the congruent condition, RT was faster in the far condition than that in the close condition (i.e., symbolic distance effect), whereas in the incongruent condition, RT was faster in the close condition than that in the far condition (i.e., reversed distance effect).

In the present study, we also asked subjects to judge which of two numbers was larger, with "larger" defined in term of numerical size (Experiment 1) or physical size (Experiment 2) in accordance with Henik and Tzelgov (1982). The main modifications of the present study were that two types of written-word numbers were involved, and the numbers were presented tachistoscopically to emphasize the aspect of indirect numerical processing. This design permits us to address the semantic processing of Arabic and written-word numbers with the direct numerical task (Experiment 1) and with the indirect numerical task (Experiment 2) simultaneously with the same stimuli and procedures except for the task requirement.

In Japanese, numbers can be written in three types of notation, Arabic (e.g., 6), Kanji (e.g., 六), and Kana (e.g., ロク). In the present study, we used all three notations because no study has so far examined all Arabic, Kanji, and Kana number processing in one experiment (Hatta, 1977, 1978). Kanji is an ideographic script, and Kana is a syllabic script (e.g., Kess & Miyamoto, 1994). Kanji numbers are somewhat similar to Arabic numbers in that the smallest units of representation (i.e., digits) are themselves each related to a meaningful concept, though Kanji words are roughly comparable to irregular words in European languages in that they are more concerned with a whole-word image (Sakurai et al., 2001). On the other hand, Kana numbers may be similar to alphabetic numbers because specific combinations of the smallest representational units (i.e., letters) convey the meaning. Kana words are comparable to regular words in that grapheme-to-phoneme correspondence is almost total (Sakurai et al., 2001). Previous studies have revealed that processing of Kanji and Kana words is partially different (e.g., Kimura, 1984; Sasanuma, Itoh, Mori, & Kobayashi, 1977; Yamadori, 2000).

In both experiments, we analyzed the effect of two factors, congruity and numerical distance, on the subjects' performance as employed by Henik and Tzelgov (1982). The results were interpreted according to the following framework. Three serial processing stages must be included in the present numerical size judgment task: the identification stage, the comparison stage, and the response stage (Dehaene, 1996). In the first stage, Arabic and written-word numbers are identified by the visual identification system. In the second stage, numbers (e.g., 2–6) are translated into the mental analogue number line (analogue number representation), and then the relative magnitude relation between numbers is computed (later comparison stage). In the response stage, the output from the comparison stage is converted into the response code, such as "left" or "right," and then the response is executed by the left or right hand. According to Dehaene's triple code model, there are separate visual identification systems for Arabic and written-word numbers (visual Arabic number form and visual word form, respectively), but the comparison stage is notation independent, as mentioned earlier. And, it is also implausible that the response stage is notation dependent.

The distance effect in Experiment 1 must occur at the comparison stage. According to Dehaene's triple code model, the distance effect can be explained by the variable overlap between the distributions associated with different numbers. As two numbers become closer, the distributional overlap is greater, and it becomes increasingly difficult to distinguish which is the larger. On the other hand, the congruity effect must reflect interactive processing between number and physical size judgment processing. In particular, in Experiment 1, it reflects the automatic physical size in numerical size processing, as opposed to the automatic number sizes in physical size processing in Experiment 2. The numerical and physical size processing can interact with each other at multiple processing stages, as do the word and color in the Stroop task (see MacLeod, 1991). However, recent studies have suggested that the congruity effect relates to a late processing stage such as the later comparison stage or the response stage (Dehaene et al., 1998; Naccache & Dehaene, 2001; Ratinckx & Brysbaert, 2002; Ratinckx, Brysbaert, & Reynvoet, 2001). Although it is difficult to interpret the distance effect in Experiment 2 at present, it is reasonable to suggest that it is also evidence of automatic numerical size processing.

EXPERIMENT 1
Numerical Size Judgment (Direct Numerical Task)

The purpose of Experiment 1 was to replicate the previous findings with the direct numerical task (i.e., the similarity of semantic representation across the three notations). In Experiment 1, Arabic, Kanji, or Kana numbers were presented, and subjects were asked to judge which of two numbers was larger in numerical size, ignoring the physical size. The critical issue was whether a similar distance effect, which suggests the existence of a common semantic representation, would be obtained across the three notations. Further, a demonstrated congruity effect might reflect automatic physical size processing in numerical size processing. If similar congruity effects are obtained across notations, these results would suggest that the representations of the three notations would also be similar at the late processing stage.

Method

Subjects. Seventy-six undergraduate and graduate students of Nagoya University, Nagoya Shukutoku University, and Daido Institute of Technology University (34 male, 42 female) participated in the experiment for course credit. Their average age was 20.8 years (*SD* = 1.67). All had unimpaired or corrected vision and were native Japanese readers and speakers. They were unaware of the purpose of the study. Experiment 1 took place at Nagoya University.

Apparatus. This experiment was run on an Apple Performa 6310 controlled by the time schedule of PsyScope (J. Cohen, MacWhinney, Flatt, & Provost, 1993). Subjects' responses were measured by a button box system of PsyScope, which can measure RT within 2 msec accuracy.

Stimuli. For Arabic and Kanji, five numbers [3(三), 4(四), 6(六), 8(八), and 9(九)] were used. Figure 1 shows a sample of the stimuli used in this study. The following eight number pairs were created: 3–4, 8–9, 4–6, 6–8, 4–8, 3–8, 4–9, 3–9. One number of each pair was of a larger size (height 24 mm, width 20. mm), whereas the other was presented in a smaller size (height 18 mm, width 15 mm) on the computer screen.

For Kana, five numbers (1, 3, 4, 6, and 8) were used because of the characteristic of Kana notation (syllable strings). To align the lengths of Kana numbers, 1(イチ), 3(サン), 4(ヨン), 6(ロク), and 8(ハチ) were used; 9 (キュウ) was not used because it consists of three letters. As a result, all numbers used for Kana notation consisted of two letters and two syllables (Figure 1). Eight number pairs were prepared: 3–4, 1–3, 4–6, 6–8, 4–8, 1–6, 3–8, 1–8. Because the physical size of one letter was the same as one Arabic or Kanji number, height and width of whole Kana numbers were twice that of one Arabic or Kanji number. As a result, one number of the pair appeared as large (height 48 mm, width 40 mm), whereas the other was presented as small (height 36 mm, width 30 mm).

Procedure. Twenty-five subjects performed the numerical size judgment with Arabic or Kanji numbers and 26 subjects performed

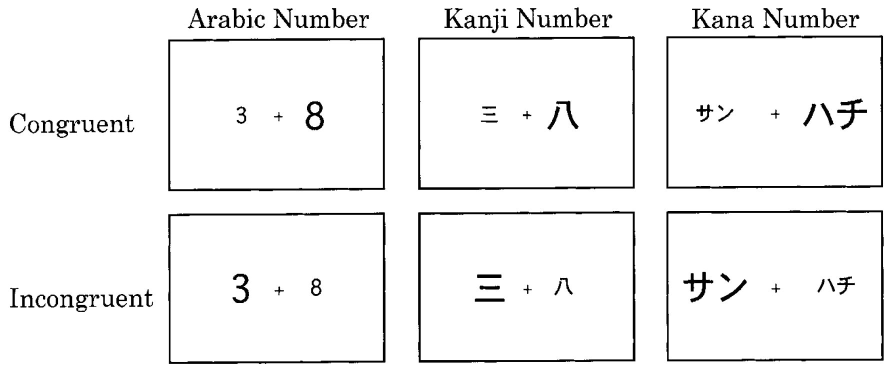

Figure 1. A sample of the stimuli used in Experiments 1 and 2.

the numerical size judgment with Kana numbers. The time schedule of trials was identical across subject groups. Each trial began with a central fixation cross which lasted for 500 msec, followed by a blank for 500 msec. After the fixation and blank, number pairs were presented for 195 msec in a horizontal orientation with the center of each number appearing 40 mm to the right or the left of center. The color of the numbers was white, and they were presented on a black background. Each trial ended with the subject's response, and the next trial followed after a blank for 500 msec. Subjects were asked to judge which of the two numbers was larger in numerical size, ignoring the physical size. They were instructed to press the button on the same side as the bigger number with the thumb of either the left or right hand. The instructions emphasized both speed and accuracy. Each task started with 20 practice trials in which the stimuli used were different from those of the test sessions.

Four blocks were created containing all eight number pairs, each comprising 32 trials. In one block, one number of a pair was presented once to the left side of the screen and once to the right side, and one number of a pair was presented once in a large size and once in a small size. The order of the number pairs in each block was randomized, and the order of the four blocks was counterbalanced across subjects by a Latin square. By means of this procedure, we obtained a total of 128 responses from each subject and were able to manipulate the two main variables, congruity (congruent vs. incongruent) and numerical distance (close vs. far) systematically. Subjects were seated 60 cm away from the monitor, and a brief rest (about 1 min) was inserted between blocks. The duration of the entire experiment was about 15 min.

Design. The variables manipulated were notation (Arabic, Kanji, or Kana), congruity (congruent vs. incongruent), and numerical distance (close vs. far). We manipulated the factor of notation between subjects, preferring to avoid a possible harmful effect of too many repeated stimuli pairs on performance of numerical judgments. The last two variables were within-subjects factors. In this study, we defined the pairs with a numerical distance of one or two unit(s) as "close" (e.g., 3–4), and the pairs with a numerical distance of four or more units as "large" (e.g., 3–8). Although it seems that the definition of distance depends on the stimuli used in previous studies, most of the researchers defined one- or two-unit pairs as close, and four- or more unit pairs as far (e.g., Dehaene, 1996; Henik & Tzelgov, 1982).

Results

Four subjects were excluded from the analysis because their error rates were higher than 15%. We computed mean RTs for correct responses for each experimental condition, excluding the responses that deviated 2 *SD* from the means. RTs of numerical size judgment were subjected to a 3 (notation) × 2 (congruity) × 2 (distance) analysis of variance (ANOVA), with notation as the between-subjects factor. Table 1 shows the mean RTs and the proportion of errors for each condition. Since the error rate was relatively low and there was no speed–accuracy tradeoff, we have simply reported RT in this article. Mean total error rate was 6.73% (SD = 3.67).

The ANOVA indicated that the main effect of notation was significant [$F(2,69) = 50.27$, $MS_e = 20{,}866.79$, $p < .001$]. Tukey's *HSD* test showed that the response to the Arabic numbers (417 msec) was quickest, and RT to Kana numbers (623 msec) was slower than that to Kanji (491 msec; $HSD = 55.43$). The congruity effect was sig-

Table 1
Experiment 1: Mean Reaction Times (RTs, in Milliseconds), Standard Errors, and Proportion of Errors (PE)

	Close		Far		Close		Far	
Notation	RT	*SE*	RT	*SE*	PE	*SE*	PE	*SE*
Arabic								
Congruent	417	14.72	374	11.18	.042	.011	.004	.003
Incongruent	460	14.24	416	11.68	.161	.023	.034	.006
Kanji								
Congruent	494	16.22	437	13.02	.070	.011	.004	.002
Incongruent	546	16.46	486	13.40	.129	.017	.048	.013
Kana								
Congruent	634	18.21	567	16.47	.108	.013	.020	.006
Incongruent	670	19.31	622	16.76	.150	.016	.038	.007

nificant (incongruent minus congruent: Arabic = 42 msec, Kanji = 50 msec, Kana = 46 msec) [$F(1,69) = 202.13$, $MS_e = 754.62$, $p < .001$]. This effect did not interact with notations ($F < 1$). The distance effect was also significant (close minus far: Arabic = 43 msec, Kanji = 58 msec, Kana = 57 msec) [$F(1,69) = 265.11$, $MS_e = 760.57$, $p < .001$], and this effect did not interact reliably with notations [$F(2,69) = 2.20$, $MS_e = 760.57$, $p > .1$]. The congruity × distance interaction was not significant [$F(1,69) = 2.96$, $MS_e = 181.58$, $p > .08$], but the three-way interaction among notation, congruity, and distance was significant [$F(2,69) = 4.94$, $MS_e = 181.58$, $p < .01$]. The simple interaction tests revealed that the interaction between congruity and distance was significant for Kana [$F(1,69) = 12.62$, $MS_e = 181.58$, $p < .01$], but not for Arabic and Kanji (both Fs < 1). Following Mori and Yoshida (1998), we conducted simple main effect tests for RT to Kana numbers with pooled mean square error and degrees of freedom. For Kana, the simple main effect test showed that the distance effect was larger in the congruent trials (67 msec) than that in the incongruent trials (48 msec), although the main effect of distance was significant in each congruent condition [$F(1,138) = 114.80$, $MS_e = 471.07$, $p < .01$; $F(1,138) = 57.70$, $MS_e = 471.07$, $p < .01$, respectively].

Discussion

The results of Experiment 1 showed that (1) overall RTs were different across notations, and (2) the congruity and distance effects with Arabic numbers were comparable to the results of Henik and Tzelgov (1982), and the pattern of these effects was similar across notations. These results are consistent with Dehaene's (1992) triple code model, according to which the difference of general RT can be explained at the identification stage. For example, in a Japanese population, there may be separate input-notation-dependent representations for Arabic, Kanji, and Kana numbers at the identification level (Kimura, 1984; Sasanuma et al., 1977; Yamadori, 2000).

In contrast with the differences in overall RT, the similar congruity and distance effects suggest that the representations after the identification stage are the same irrespective of notations. According to Dehaene's model, both Arabic and written-word numbers are translated into a common semantic representation, analogue magnitude representation, whereby his model can predict our results. That is, Arabic, Kanji, and Kana numbers were translated into a common semantic representation.

In addition to these main effects, however, an interaction between congruity and distance was obtained with Kana numbers only. The distance effect was larger in the congruent trials than in the incongruent trials. This interaction results in a relatively slower RT in the close trials in the congruent conditions. This result may suggest that the representation of Kana numbers is different from that of Arabic and Kanji after the identification stage. However, since the pattern of results is very similar across notations, we tentatively concluded that the results of Experiment 1 suggest that Arabic, Kanji, and Kana numbers could be represented equally after the identification stage, which supports the assumption of a common semantic representation.

EXPERIMENT 2
Physical Size Judgment
(Indirect Numerical Task)

The aims of Experiment 2 were (1) to investigate whether all Arabic, Kanji, and Kana numbers are translated into semantic representations automatically and (2) to verify whether the assumption of a common semantic representation is also valid with the indirect numerical task. For these purposes, we changed the task requirement from numerical size judgment to physical size judgment in Experiment 2.

In Experiment 2, Arabic, Kanji, or Kana numbers were presented, and subjects were asked to judge which of a pair of numbers was larger in physical size, ignoring numerical size. Therefore numerical information was not relevant to the task requirement. The critical issue was whether similar patterns of congruity and distance effects, which are indices of automatic numerical size processing, would be obtained across the three notations. Like Henik and Tzelgov (1982), we predicted an interaction between the congruity and distance effects with Arabic numbers. If the same pattern of congruity and distance effects was observed across notations, this result would suggest that the representations of the three notations are similar after the identification stage, even using the indirect numerical task.

Method

Subjects. Seventy-three undergraduate and graduate students of Nagoya University, Nagoya Shukutoku University, and Daido Industrial Technology University (34 male, 39 female) participated in the experiment for course credit. Average age was 20.8 years ($SD = 1.70$). All had unimpaired or corrected vision and were native readers and speakers of Japanese. They were unaware of the purpose of the study. Experiment 2 was also run at Nagoya University.

Procedure. The apparatus, stimuli, procedure, and design of the experiment were identical to those of Experiment 1, except for task requirements. In Experiment 2, subjects were required to judge which of two numbers was larger in physical size, ignoring numerical size.

Results

One subject was rejected for failing to comply with the instructions. We computed mean RTs for correct responses, excluding those responses that deviated two or more standard deviations from the mean for each experimental condition. RTs of physical size judgment were subjected to a 3 (notation) × 2 (congruity) × 2 (distance) ANOVA, with notation as the between-subjects factor. Table 2 shows the mean RTs and the proportion of errors for each condition. Mean total error rate was 2.45% ($SD = 2.54$).

Table 2
Experiment 2: Mean Reaction Times (RTs, in Milliseconds), Standard Errors, and Proportion of Errors

	Close		Far		Close		Far	
Notation	RT	*SE*	RT	*SE*	PE	*SE*	PE	*SE*
Arabic								
Congruent	325	10.28	319	9.46	.020	.006	.005	.002
Incongruent	327	10.81	338	11.16	.025	.006	.078	.016
Kanji								
Congruent	328	8.50	329	8.97	.020	.007	.008	.003
Incongruent	332	9.32	333	8.99	.016	.005	.029	.006
Kana								
Congruent	312	8.11	317	8.61	.020	.008	.025	.032
Incongruent	312	8.44	315	8.51	.025	.038	.026	.043

The ANOVA indicated that the main effect of notation was not significant (Arabic = 327 msec, Kanji = 330 msec, Kana = 314 msec) [$F(2,69) = 0.89$, $MS_e = 8{,}133.76$, $p > .4$]. The congruity effect was significant [$F(1,69) = 21.54$, $MS_e = 71.91$, $p < .01$], but this effect interacted with notation [$F(2,69) = 11.30$, $MS_e = 71.91$, $p < .01$]. The simple main effect test showed that the congruity effect was significant for Arabic (12 msec) and Kanji (4 msec) [$F(1,69) = 38.80$, $MS_e = 71.91$, $p < .01$; $F(1,69) = 5.14$, $MS_e = 71.91$, $p < .03$, respectively], but not for Kana (−1 msec) [$F(1,69) = 0.21$, $MS_e = 71.91$, $p > .6$]. To endorse the validity of the congruity effect, we conducted another 2 (congruity) × 2 (distance) ANOVA for error rates of Kanji numbers, which revealed that the error rate was higher in the incongruent trials ($M = 2.2\%$, $SE = .004$) than in the congruent trials ($M = 1.4\%$, $SE = .004$) [$F(1,23) = 4.77$, $MS_e = 0.0004$, $p < .05$]. This error rate result was consistent with that for RT, indicating a significant congruity effect.

The main effect of distance was significant [$F(1,69) = 6.98$, $MS_e = 64.14$, $p < .03$]. This effect did not interact with notation ($F < 1$). As Table 2 shows, however, the results were more complicated. The congruity × distance interaction was significant [$F(1,69) = 9.58$, $MS_e = 54.42$, $p > .01$], and the three-way interaction among notation, congruity, and distance was also significant [$F(2,69) = 12.13$, $MS_e = 54.42$, $p < .01$]. The simple interaction tests revealed that the congruity × distance interaction was significant for Arabic [$F(1,69) = 33.40$, $MS_e = 54.42$, $p < .01$], but not for Kanji and Kana numbers [$F(1,69) = 0.04$, $MS_e = 54.42$, $p > .8$; $F(1,69) = 0.39$, $MS_e = 54.42$, $p > .5$, respectively]. For Arabic numbers, the simple main effect test showed that the symbolic distance effect (6 msec) was observed in the congruent condition [$F(1,138) = 7.26$, $MS_e = 59.28$, $p < .01$], whereas a reversed distance effect (−11 msec) was revealed in the incongruent condition [$F(1,138) = 26.38$, $MS_e = 59.28$, $p < .01$].

Discussion

Our findings on Arabic numbers were consistent with those of Henik and Tzelgov (1982). We also obtained an interaction between congruity and distance. RT for far trials was faster than that for close trials in the congruent condition (i.e., symbolic distance effect), whereas RT for close trials was faster than that for far trials in the incongruent condition (i.e., reversed distance effect). However, the results with Kanji and Kana numbers were not found to be similar. Only a congruity effect was observed with Kanji numbers, whereas neither congruity nor distance effects were found with Kana numbers. In other words, we demonstrated different semantic processing across notations in the indirect numerical task.

The results for Kana numbers (i.e., no effects of congruity and distance) indicated nonsemantic processing of Kana numbers. This result is inconsistent with that of Dehaene and Akhavein (1995). The disappearance of the semantic process might be attributable to a lower level processing of Kana numbers (see General Discussion). In the indirect task, Kana numbers might be processed as visual objects (Algom, Dekel, & Pansky, 1996; Pansky & Algom, 2002). Otherwise, Kana numbers processing might end at the phonological level (Brysbaert, 2001; Fias, 2001; Fias, Reynvoet, & Brysbaert, 2001).

The different pattern of results between Arabic and Kanji numbers suggests that these numbers could be represented in qualitatively different ways after the identification stage. Although it is tentative, the finding could be explained by the following: Arabic numbers can be finely (accurately) represented at the semantic level, and an analogical code with the relative distance information between numbers is assigned for each number of a pair at the later comparison stage. In such a case, codes extracted from a far pair (e.g., 3–9) should have a greater influence on the performance of physical size judgment than those extracted from a close pair (e.g., 3–4). That is, compatibility (or incompatibility) between numerical and physical size is larger in far pairs than in close pairs. In the congruent trials, such codes would promote the physical size judgment. However, such codes would interfere with the physical size judgment in the incongruent trials. As a result, we might observe a symbolic distance effect in congruent trials, but a reversed distance effect in incongruent trials.

Another way to explain the pattern would be to suggest that Kanji numbers might be coarsely represented at the semantic level, in which case only a categorical code without relative distance information between numbers (e.g., "large" or "small") is assigned for each number of the pair at the later comparison level. In other words, the Kanji numbers were represented sufficiently accurately for them to be categorized as "large" or "small," but the code assigned at the later comparison level was not precise enough so that the number distance could have a different effect on the performance of physical size judgment. For instance, consider the close pair "3–4" and the far pair "3–8." A categorical code such as "small" would be extracted from the 3 in each pair, and "large" from either the 4 or the 8. If the categorical code were assigned at the later comparison stage, the compatibility between numerical and physical size would not be different between the far pair and the close pair. In this case, only a congruity effect could be observed.

In short, at present, we infer that the qualitative difference of semantic representation between Arabic (fine code) and Kanji numbers (coarse code) at the comparison stage could produce the different pattern of results between Arabic and Kanji numbers (Beeman, 1998; Henik & Tzelgov, 1982; Koechlin et al., 1999: Kosslyn, Chabris, Marsolek, & Koening, 1992).

GENERAL DISCUSSION

The main findings of the present study were the following: (1) With the direct numerical task, parallel congruity and distant effects were found for all three notations, though overall RT was different across notations; and (2) with the indirect numerical task, congruity and numerical distance influenced the performance of physical judgments depending on the notations. We will try to indicate how Dehaene's (1992) triple code model can explain our findings and suggest how the model should be modified to account for our findings below.

The results of Experiment 1 are consistent with Dehaene's triple code model. The difference of overall RTs across notations could have occurred at the identification level. It is possible that the Japanese population might have multiple visual identification systems for Arabic, Kanji, and Kana numbers (Kimura, 1984; Sasanuma et al., 1977; Yamadori, 2000). The similar pattern of congruity and distance effect across notations suggests that the representations after the identification stage are similar across notations. This can also be explained within Dehaene's model because his model assumes that all numbers access a common semantic representation, analogue magnitude representation, regardless of input notations.

However, the results of Experiment 2 cannot easily be explained by Dehaene's triple code model. According to Dehaene, both Arabic and written-word numbers are automatically translated into a common semantic representation (Dehaene & Akhavein, 1995). However, in our study, Kana numbers, unlike Arabic and Kanji numbers, were not processed semantically in the indirect numerical task. This result suggests that at least the assumption of automatic semantic activation should be limited in the case of Kana numbers. As a possible modification, one could assume that the connective strength between notation-dependent (i.e., visual number form) and semantic representations (i.e., analogue magnitude representation) can vary for each notation. That the connection is stronger for Arabic and Kanji numbers than for Kana numbers seems to be valid (for Arabic vs. written-word numbers, see Fias, 2001; Fias et al., 1996; Ratinckx et al., 2001). As a result, Kana numbers might be processed as visual objects in only our indirect numerical task (Algom et al., 1996; Pansky & Algom, 2002).

Another possible explanation might be that the dominance of processing pathways differs across notations. There is considerable evidence that semantic access of Kana words is mediated by the phonological representation, whereas Kanji words can access semantic representation directly (e.g., Yamada, 1998). Further, Fias et al. (2001) demonstrated that Arabic number naming is semantically mediated, whereas written-word number (alphabetic number) naming is phonologically mediated. Therefore, the pathway with mediation of a phonological representation might be dominant for Kana numbers (i.e., visual number form–verbal word frame–analogue magnitude representation), whereas the direct pathway could be dominant for Arabic and Kanji numbers (i.e., visual number form–analogue magnitude representation). Thus, as alphabetic numbers, Kana numbers might be translated up to a phonological representation in our indirect numerical task (Brysbaert, 2001; Fias, 2001; Fias et al., 2001).

It is more difficult to reconcile the different pattern between Arabic and Kanji numbers in Experiment 2 with Dehaene's triple code model (and also McCloskey's model). Dehaene assumes a common semantic representation for Arabic and written-word numbers. Because it is implausible that the response stage is notation dependent, it is likely that representations after the identification stage are the same across all notations. However, our results with the indirect numerical task revealed that such an assumption cannot apply to Arabic and Kanji number processing. This result demonstrated that number cognition is supported by a more complex mechanism, as Campbell and Clark (1988) proposed, and suggests that there might be separate semantic representations for Arabic and Kanji numbers.

How can we explain the discrepancy between the results of Experiment 1 (i.e., suggesting a common semantic representation) and Experiment 2 (i.e., suggesting separate semantic representations for Arabic and Kanji numbers)? Koechlin et al. (1999) examined how Arabic numbers, written-word numbers (alphabetic numbers), and dot patterns can be represented at the semantic level with the masked prime paradigm of numerical size judgment (i.e., less attentive processing condition). The most critical index of semantic processing was the quantity priming effect, which refers to the finding that RT decreases when the distance between prime and target numbers is less. They hypothesized that if there is a common semantic representation for all notations, as Dehaene proposed, then quantity priming should be observed both within and across notations. However, their results were inconsistent with such a hypothesis. In their Experiment 1, quantity priming occurred within each notation (Arabic, written-word, and dot patterns) as well as across Arabic and written-word notations, but not across Arabic and dot pattern. In their Experiment 2, quantity priming was still observed within Arabic or written-word notation, but no cross-notation priming was found between them. Therefore they concluded that there are separate semantic representations for each notation (Arabic, written-word, and dot patterns) and proposed a tentative model of number cognition.

According to the tentative model of Koechlin et al. (1999), the semantic system normally functions as unitary, but can be broken down into smaller input-notation-dependent subsystems under certain experimental conditions (e.g., less attentive processing condition as the masked prime paradigm). They continued:

> When a number is presented in a given notation, say as an Arabic digit, it initially activates only a fraction of the quantity representation, namely the quantity subsystem devoted to Arabic inputs. Rapidly, the activation propagates to other quantity- and notation-specific subsystems. Eventually, the network falls down into a steady state of activity that represents numerical quantity independent of the notation that was initially used to activate it. However, the first stages of its activation depended on input notation. (pp. 1901–1902)

Our findings in Experiment 2 are consistent with the tentative model of Koechlin et al. (1999). The rapid activation propagation between Arabic and Kanji might result in a similar pattern of congruity and distance effects between Arabic and Kanji numbers (and also Kana numbers) in Experiment 1 (direct numerical task). In Experiment 2, different activation between Arabic and Kanji numbers in the semantic subsystem was revealed with the indirect numerical task (i.e., less attentive processing condition). However, the main effect size was smaller in Experiment 2 than in Experiment 1, which might reflect the fact that activation in the input-notation-dependent semantic subsystem might be relatively weak.

Finally, we acknowledge the limitations of the present experimental design with regard to conclusions about automatic semantic activation of Arabic and Kanji numbers. Algom and colleagues pointed out that factors associated with the stimulus can produce interference or facilitation in Garner and Stroop-like paradigms (e.g., Algom et al., 1996; Dishow-Berkovits & Algom, 2000; Pansky & Algom, 1999; Pansky & Algom, 2002). For instance, Pansky and Algom (1999) demonstrated that larger Stroop effects could be observed with a many-valued irrelevant dimension than with a binary-valued irrelevant dimension. They argued that a many-valued stimulus dimension (e.g., six values) is more informative than a binary-valued dimension, and that a many-valued dimension can better capture attention. In short, Algom and colleagues argued that Stroop and Garner effects do not reflect on automatic processing, but only on attentive processing of an irrelevant dimension of the stimulus.

In the present study, there were five values for the numerical dimension, whereas there were only two values for the physical dimension. Because of this mismatch (or imbalance), the numerical dimension might have moderately captured attention even when the indirect numerical task was introduced. In other words, the limitations of the present experimental design might have resulted in an overestimation of the automatic semantic activation of numbers. If we borrow Algom's definition, our design may have overstated the automatic semantic activation of Arabic and Kanji numbers on the present data. Nevertheless, the importance of our findings in Experiment 2—no semantic activation of Kana numbers only and a qualitative difference in semantic representation between Arabic and Kanji numbers—should not be affected by the limitations of the present experimental design, given that the same design served for all notations.

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