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A Reading Model from the Perspective of Japanese Orthography: Connectionist Approach to the Hypothesis of Granularity and Transparency

Mutsuo Ijuin, PhD[1] and Taeko N. Wydell, PhD[2]

Abstract

This study presents a computer simulation model of reading in Japanese syllabic kana and morphographic kanji. The model was based on the simulation model developed by Harm and Seidenberg for reading in English. The purpose of building the current model was to verify the validity of the hypothesis of granularity and transparency (HGT) postulated by Wydell and Butterworth, focusing on the granularity dimension. The HGT was developed in order to explain the behavioral dissociation between excellent reading skills in Japanese and poor reading skills in English of an English–Japanese bilingual individual as well as the relatively low incidence of developmental dyslexia in Japan. The current model was successful in simulating the granularity dimension of the HGT. The study also identified several limitations, which need to be addressed in future research.

Keywords

connectionist model, Japanese kanji, kana, hypothesis of granularity and transparency

It has been reported that the prevalence of dyslexia in the English-speaking world is 10% to 12% (e.g., Shaywitz, Shaywitz, Fletcher, & Escobar, 1990; Snowling, 2000), thus forming a large minority group. Extensive research has been conducted in order to ascertain the causes of dyslexia. For example, Ramus (2003) reviewed the empirical studies in relation to the major deficit theories accounting for the causes of developmental dyslexia, such as deficits in, for example, auditory processing (in particular, rapid or temporal processing; e.g., Tallal, 1980; Share, Jorm, MacLean, & Matthews, 2002); visual processing, including magnocellular dysfunction (Stein, 2014); motor control (Wolff, 2002) including cerebellar dysfunction (Nicolson, Fawcett, & Dean, 2001); general sensorimotor processing (Laasonen, Service, & Virsu, 2001); and phonological processing (Snowling, 2000). Phonological deficits are said to be highly heritable, whereas auditory and visual deficits are not (e.g., Olson & Datta, 2002); Ramus (2003) concluded that "although the phonological deficit is still in need of a complete cognitive and neurological characterization, the case for its causal role in the etiology of the reading and writing disability of the great majority of dyslexic children is overwhelming" (p. 216).

This is particularly true for English because of the characteristics of the English orthography. Studies in English have shown that the computation of phonology from orthography does occur for units smaller than the word, and that words containing an inconsistent "word body" or "rhyme," as in *-int* in *pint* versus *hint* or *lint*, are disadvantaged in accuracy and/or speech over those words containing a consistent word body or thyme, as in *-ink* in *link* or *mink* (e.g., Andrews, 1982; Jared, McRae & Seidenberg, 1990; Parkin, 1984). It was Glushko (1979) who argued that consistency rather than rule-defined regularity could better explain the empirical results. For example, although *five* is a regular word by grapheme–phoneme correspondence rules, its spelling–sound relationship is inconsistent with orthographically similar words, such as *give*. Moreover, this consistency effect is stronger for low-frequency words (e.g., Andrews, 1982; Cortese & Simpson, 2000; Jared, 2002; Jared et al., 1990; Plaut, McClelland, Seidenberg, & Patterson, 1996).

In a similar vein, Frost and Katz (1989) investigated "orthographic depth," which postulated that the relationship between spelling and phonology in the language

[1]Prefectural University of Hiroshima, Japan
[2]Brunel University London, United Kingdom

Corresponding Author:
Mutsuo Ijuin, Department of Communication Sciences and Disorders, Faculty of Health and Welfare, Prefectural University of Hiroshima, 1-1 Gakuen-cho, Mihara-shi, Hiroshima 723-0053, Japan.
Email: ijuin@pu-hiroshima.ac.jp

determines the rate and accuracy of reading, that is, "simple isomorphic connections between graphemes and phonemes in Serbo-Croatian, but more complex, many-to-one connections in English" (p. 302). The former orthography tends to produce shorter response times (RTs) and more accurate responses in reading. Thus, in a continuum of orthographic depth (Frost, Katz, & Bentin, 1987), English is often considered a deep/opaque orthography: The computation of phonology from print is not always consistent, unlike shallow/transparent orthographies, such as Finnish (Wydell, Vuorinen, Helenius, & Salmelin, 2003) or Italian (Paulesu et al., 2001).

Further, a high or low incidence of developmental dyslexia, especially phonological dyslexia, seems to depend on the characteristics of the orthography. That is, opaque/deep orthographies (e.g., English) produce a higher incidence of phonological dyslexia than more transparent/shallow orthographies (e.g., Italian, for which the prevalence of dyslexia is said to be 3.1% to 3.2%; Barbiero et al., 2012).

Japanese Orthography and Reading Processes

The Japanese writing system uniquely consists of two qualitatively different scripts: *morphographic kanji*, derived from Chinese characters, and two forms of *syllabic kana* (hiragana and katakana), both derived from kanji characters (see Wydell & Kondo, 2015). These two different scripts are used to write different classes of words: kanji for nouns and the root morphemes of adjectives and adverbs, katakana for the large number of foreign loan words (e.g., カーテン /ka-a-te-n/ [curtain]), and hiragana for function words (e.g., しかし /shi-ka-shi/ [but]), inflected parts of verbs (e.g., 学ぶ /mana-bu/ [learn]), adjectives (e.g., 美しい /utsuku-shi-i/ [beautiful]), and adverbs (e.g., 忙しく /isoga-shi-ku/ [busily]).[1] The syllabic kana has a transparent relationship between a kana character and its pronunciation; that is, one character consistently represents a whole mora (syllable-like unit). It is known that Japanese children master both kana scripts very quickly; most children learn the hiragana scripts even before they start primary school education (Sakamoto & Makita, 1973).

Because of the transparent nature of the computation of phonology from kana, behavioral studies with Japanese adults have shown that the optimal way of reading in kana is a simple character-to-sound conversion (i.e., sublexical) processing as with other shallow orthographies (Rastle, Havelka, Wydell, Coltheart, & Besner, 2009, for Japanese kana and Serbian; Wydell et al., 2003, for Finnish; Zoccolotti et al., 2005, for Italian). Note, however, that some studies also showed the involvement of whole-word (i.e., lexical) reading processes in kana (Besner & Hidebrant, 1987).

In contrast, the relationship between a kanji character and its pronunciation is one to many, hence opaque, because each character is an orthographic element that cannot phonetically be decomposed in the way that an alphabetic word can. There are no separate components of a character that correspond to the individual phonemes (Wydell, Butterworth, & Patterson, 1995). Further, most kanji characters have one or more *on-readings* (of Chinese origin) and a *kun-reading* (of Japanese origin). Some characters have no kun-reading, but for those that have, the kun-reading is almost always the correct reading when this character constitutes a word. For example, the character 歌, pronounced as /uta/ in kun-reading, is a single-character word meaning "song." The same kun-reading can be seen in two-character words, such as 歌声 /uta-goe/ (singing voice). However, the same character is also pronounced as /ka/ in on-reading, as in 歌手 /ka-shu/ (singer; Wydell et al., 1995). Therefore kanji learning is essentially by rote: Children are introduced to new kanji characters in texts. The learning method that is in common use is repeated writing or rehearsal by writing (e.g., Naka & Naoi, 1995). In Japan, common core curricula are used during the period of compulsory education, that is, 6 years of primary school, ages 7 to 12, and the subsequent 3 years of junior high school, ages 13 to 15. During the period of compulsory education, children across Japan are introduced to just over 2,000 different kanji characters prescribed by the Ministry of Education and Science. Note, however, that adults require around 3,000 characters for most everyday literacy activities (e.g., reading a national newspaper; Wydell & Butterworth, 1999).

Behavioral studies with Japanese adults have shown that kanji reading also involves both whole-word (lexical) and character-level (sublexical) processes. For example, Shibahara, Zorzi, Hill, Wydell, and Butterworth (2003) showed a significant imageability effect during kanji reading (i.e., high-imageability words produced faster naming latencies/higher accuracy than low-imageability words), thus indicating the involvement of a whole-word (lexical) reading process. In contrast, Patterson, Suzuki, Wydell, and Sasanuma (1995) revealed errors of legitimate alternative reading of components (LARC) in naming two-character kanji words in a patient with progressive aphasia due to dementia. In the LARC errors, the pronunciation of one or more components is inappropriate for the target word but is nonetheless legitimate and often more typical for words containing the character. That is true for many kanji characters; for example, the before-mentioned 歌声 /uta-goe/ can be read as /ka-sei/, a nonword, which is defined as a LARC error. These LARC errors thus indicate character-by-character (sublexical) reading processes. Note, however, that Patterson et al. did not interpret the data in terms of the lexical versus sublexical reading processing dichotomy. Wydell and Kondo (2015) in their review paper concluded that although reading morphographic Kanji involves both

whole-word (lexical) and character-level (sublexical) reading processes, kanji may require a greater weighting for the whole-word-level contribution in the computation of phonology from orthography. This is precisely because the relationship between a kanji character and its pronunciation is opaque. Similarly, the above-mentioned orthographic depth hypothesis (Katz & Frost, 1992) also states that in all orthographies, both lexical and sublexical processes take place in reading, but orthographic depth (i.e., complexity, inconsistency, or incompleteness of sublexical correspondences) affects their ratio.

Prevalence of Developmental Dyslexia in Japanese

It was often reported that the incidence of reading difficulties (dyslexia) in Japanese was low, for example, 0.1% (Makita, 1968) or less than 2% (Kokuritsu Tokushu-Kyoiku Sougou-Kenkyujyo, 1996). These studies, however, were typically conducted employing questionnaire-based surveys and therefore lacked objective measures. Therefore Uno, Wydell, Haruhara, Kaneko, and Shinya (2009) tested 495 Japanese primary school children in Japan on their reading/writing and other cognitive skills, including phonological awareness. The results showed that the percentages of children who had reading difficulties in syllabic hiragana and katakana and morphographic kanji were 0.2%, 1.4%, and 6.9%, respectively—these figures were still significantly lower than those reported in studies in English (10%–12%). Japanese researchers usually attribute these reading difficulties to visual or visuospatial rather than phonological processing problems (e.g., Kaneko et al., 1997). With similar findings in Chinese (another morphographic orthography), Wei et al. (2014) revealed that although orthographic, phonological, and morphological awareness skills predicted reading success in Chinese primary school children, orthographic awareness skills played the most dominant role in Chinese reading.

These findings lend support to the view that readers of some orthographies are more prone to dyslexia, especially phonological dyslexia. For example, Landerl, Wimmer, and Frith (1997) argued that the discrepancy in the prevalence of dyslexia in the different orthographies might primarily be due to the way in which phonology is computed from orthography. In reading English, a finer-grain processing of the orthography-to-phonology mapping is required (e.g., Treiman, Mullenix, Bijeliac-Babic, & Richmond-Welty, 1995). Therefore it is theoretically possible to see a disassociation between excellent reading skills in Japanese and poor reading skills in English in an English–Japanese bilingual individual. Indeed, a case study of such an individual, AS, was published by Wydell and Butterworth (1999). AS's reading skills in Japanese kana and kanji at age 16 were as good as those of the Japanese university students; however, his performance on reading/phonological tasks in English was significantly poorer than English and Japanese controls. Wydell and Kondo (2003)'s follow-up study on AS showed that his fundamental phonological deficit, which led to his phonological dyslexia in English, persisted into young adulthood (as shown in Figure 1).

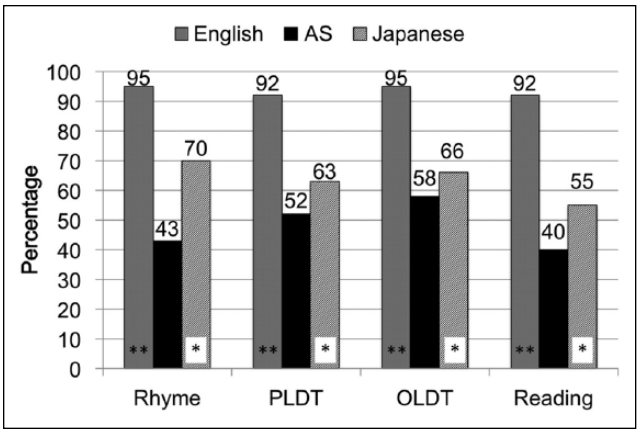

Figure 1. Reading/phonological test performance by AS and the English and Japanese control participants from Wydell and Kondo (2003).
Note. AS's performance is not only worse than that of the English control participants but also worse than that of the Japanese control participants. Rhyme = rhyme judgments; PLDT = phonological lexical decisions; OLDT = orthographic lexical decisions (spell check); reading = reading aloud of the stimuli used in PLDT. $^{*}p < .05$. $^{**}p < .01$.

To account for this behavioral dissociation, Wydell and Butterworth (1999) advocated the hypothesis of granularity and transparency (HGT), which postulated that orthographies can be described in two dimensions—transparency and granularity—with the predictions that phonological dyslexia would be rare in two conditions: (a) orthographies where print–sound translation is transparent (one-to-one), regardless of the level of translation (e.g., phoneme, syllable, character), and (b) even in opaque orthographies, if the smallest orthographic unit representing sound is coarse (i.e., larger grain size, such as a whole character/word). Thus any orthography used in any language can be placed in the transparency–granularity orthogonal dimension, as illustrated in Figure 2, and any orthography that falls into the shaded area in the figure should not give rise to a high incidence of phonological dyslexia.

Model of Reading in Japanese Kana and Kanji: Connectionist Approach to the HGT

As discussed, there are many studies investigating orthographic transparency and reading competency/literacy development (Frost et al., 1987; Paulesu et al., 2001; Wydell & Kondo, 2015). However, research investigating orthographic

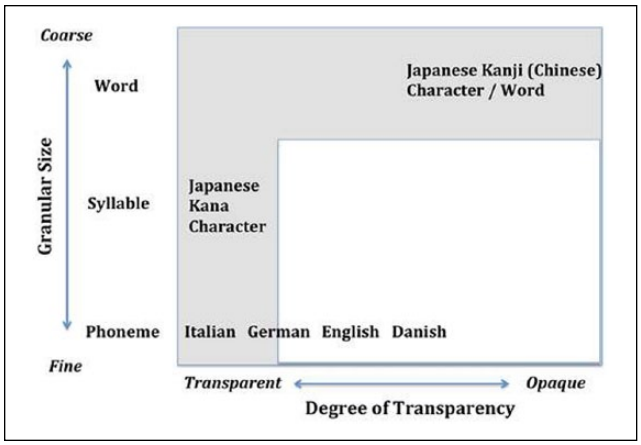

Figure 2. Hypothesis of granularity and transparency (adapted from Wydell & Butterworth, 1999).

granularity and reading competency/literacy development is not readily available, except for Wydell and Butterworth (1999; see Ziegler & Goswami, 2005, for further discussion on this topic). The granularity dimension was introduced in the HGT in order to account for AS's superior reading skills in Japanese, since the transparency dimension alone cannot explain these.

In this simulation, therefore, the focus was placed on the granularity dimension. Further, the granular size is represented by the number of morae per character, and hence the more morae a character has, the higher the performance should be. The rationale of this is as follows: In equating the transparency of the kana and kanji, naming latency differences between them should arise from the differences in the granular size, and therefore it was predicted that the reading latency of kanji (with larger granularity) should be shorter than that of kana (with smaller granularity). Accuracy should be higher for kanji than for kana. This could then explain why poor phonological awareness skills may not necessarily be detrimental to kanji reading as well as the low prevalence of developmental (phonological) dyslexia.

Method

Network Architecture

The network's task is to compute the pronunciations of kana and kanji characters directly from their written forms. Figure 3 shows the architecture of the network, which was based on the architecture developed by Harm and Seidenberg (1999).

In the current implementation, the input layer of the network was a set of 360 orthographic units, one for each kana or kanji character. This orthographic layer consists of 71 hiragana units, 71 katakana units, and 218 kanji units. These were fully connected to an intermediate layer

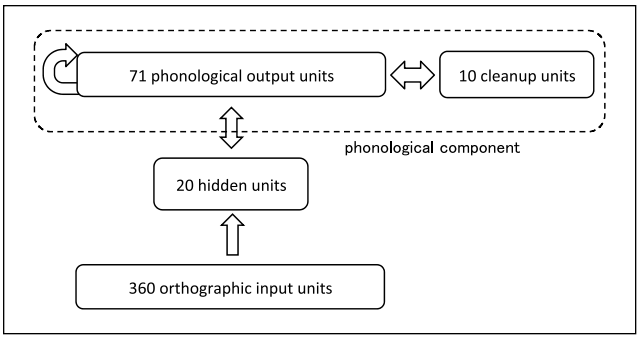

Figure 3. The architecture of the attractor network.

of 20 hidden units, which in turn were fully connected to the phonological layer. In phonology, the pronunciation of each character was represented by a sequence of morae. The phonological layer consists of 71 phonological units, one for each mora. Each phonological unit is connected to every other phonological unit not including itself. In addition, these phonological units were also connected to a set of 10 cleanup units, which receive connections from, and send connections to, the phonological units. These cleanup units have bidirectional relationships with phonological units, that is, receiving activation from and sending activation back to the phonological units, and the cleanup units permit the encoding of higher-order phonological dependencies rather than those achieved by direct connections among phonological units alone (Hinton & Shallice, 1991; Plaut & Shallice, 1993). In the current simulation, following Harm and Seidenberg (1999), we collectively referred to the phonological layer, cleanup layer, and the weights between the two layers as the "phonological component."

Training Corpus

As a training corpus, we used 142 kana characters (71 hiragana and 71 katakana) and 218 kanji characters. In this corpus, each kana character corresponds to one mora of spoken Japanese; each kanji character comprised one to four morae (one mora, 37 characters; two morae, 145 characters; three morae, 35 characters; four morae, one character). All kana characters consist of modern kana usage characters, excluding characters that correspond to contracted sounds (e.g., /kyo/) and geminate consonants (e.g., /kitte/). All 218 kanji characters have the following characteristics:

1. All are kun-reading (of Japanese origin) words, and thus each character has a single pronunciation.
2. The age of acquisition of the kanji characters (Amano & Kondo, 1999) is below Grade 6 (age 12 years) of primary school education (as described previously, Japanese primary school children are

introduced to a set of different kanji characters at every grade),
3. As with the kana characters, the kanji characters that correspond to contracted sounds or geminate consonantal sounds are excluded.
4. Kanji characters with same mora repetitions are excluded (e.g., 母 /ha-ha/, meaning "mother," or 心 /ko-ko-ro/, meaning "mind").
5. Kanji characters whose constituent mora pronunciation can make another word by exchanging the order of morae are excluded (e.g., 坂 /sa-ka/, meaning "slope" → 傘 /ka-sa/, meaning "umbrella").

For given orthography-phonology representations and characteristics of the training corpus, the only difference between kana and kanji is the mean number of morae per character in the current simulation (kana, 1.0 mora per character; kanji, 2.0 morae per character). In terms of the HGT, the degree of transparency between kana and kanji is the same (both having a single pronunciation), but the degree of granularity is different.

Training Method

The network used the same training method as the one developed by Harm and Seidengberg (1999). Like a real human child, the network first gained the phonological knowledge before any orthographic information was introduced. That is, the phonological component in Figure 3 was trained to retain the phonological pattern of the target pronunciation in the absence of external input. In this phonological task, the phonological component was trained with all 360 characters' pronunciation in the training corpus.

Normal reading model. After the phonological component had been trained with the phonological knowledge, connecting orthographic input units to phonological components through a set of hidden units took place, and thus the entire reading network (see Figure 3) was trained to read all kanji and kana characters. Following Harm and Seidengberg (1999), we introduced the interleaved training method into the learning-to-read task. During the reading task, the network was also trained on the phonological task. A random number generated which task the network was trained on. In the current simulation, on 80% of the trials, the network was trained on the reading task, and on 20%, it was trained on the phonological retention task.

In this simulation, no manipulation took place to modulate weight changes according to the frequency of the characters or the frequency (token) of the morae in the training corpus. Each mora appeared two (e.g., /re/) to 28 (e.g., /ka/) times in each training epoch in the phonological and reading task. Each character appeared only once in each training epoch in the reading task.

Developmental dyslexia model. In this model, we simulated developmental dyslexia by disrupting the phonological representation before training the network to read. The way we simulated the developmental dyslexia model is identical to that of Harm and Seidenberg (1999). The phonological impairment involved the lesioning of the connections within the phonological component by injecting Gaussian noise ($\sigma = 0.0125$) onto the weights during training individuals to read characters. In each model, we built a total of 20 networks, each of which was provided random weights at initialization and trained for 40,000 epochs.

Results

The response of the network is simply the concatenation of all active phonological units with a state above 0.5. Figure 4 shows the performances of a typical normal network and a typical dyslexia network on kana and kanji characters over the course of training.

After 40,000 training epochs, each of 20 normal reading networks correctly pronounced all of the 360 kana and kanji characters in the training corpus. Performance on kanji characters improves more rapidly than on kana; over 97.7% of kanji characters are pronounced correctly by epoch 25,000, and kana characters are at 66.9% correct at the same epoch. To ensure the reliability of this data, probit analysis was applied to each development curve of all 20 networks, estimating the number of epochs needed to reach 50% correct for each script. Estimated results showed that the mean number of epochs for kanji was 17,398 and that for kana was 22,801. Thus, the networks learned significantly faster on kanji than on kana, $t = 38.58$, $df = 19$, $p < .001$.

In contrast, after 40,000 training epochs, none of the 20 dyslexia networks were able to correctly pronounce all of the 360 kana and kanji characters. At 40,000 epochs, the accuracy (i.e., mean percentage correct) for reading kanji characters was 85.71%, and that for reading kana characters was 68.73%. As with the normal model, probit analysis was applied to each development curve of all 20 dyslexia networks, estimating the number of epochs required to reach 50% correct for each script. Estimated results showed the mean number of epochs for kanji was 19,008 and that for kana was 25,392; the dyslexia networks also learned significantly faster with kanji than with kana, $t = 45.20$, $df = 19$, $p < .001$. These results indicate the advantages of kanji over the kana characters and show that kanji is more robust to lesioning of the phonological component.

Table 1 shows the mean cycles (RTs) of 20 normal and 20 dyslexia networks and the mean percentage correct of 20 dyslexia networks in pronouncing hiragana, katakana, and kanji characters at 40,000 epochs.

The cycles were submitted to a 2 × 3 analysis of variance (ANOVA) with model type (normal and dyslexia) as a between-subjects and script (hiragana, katakana, and kanji)

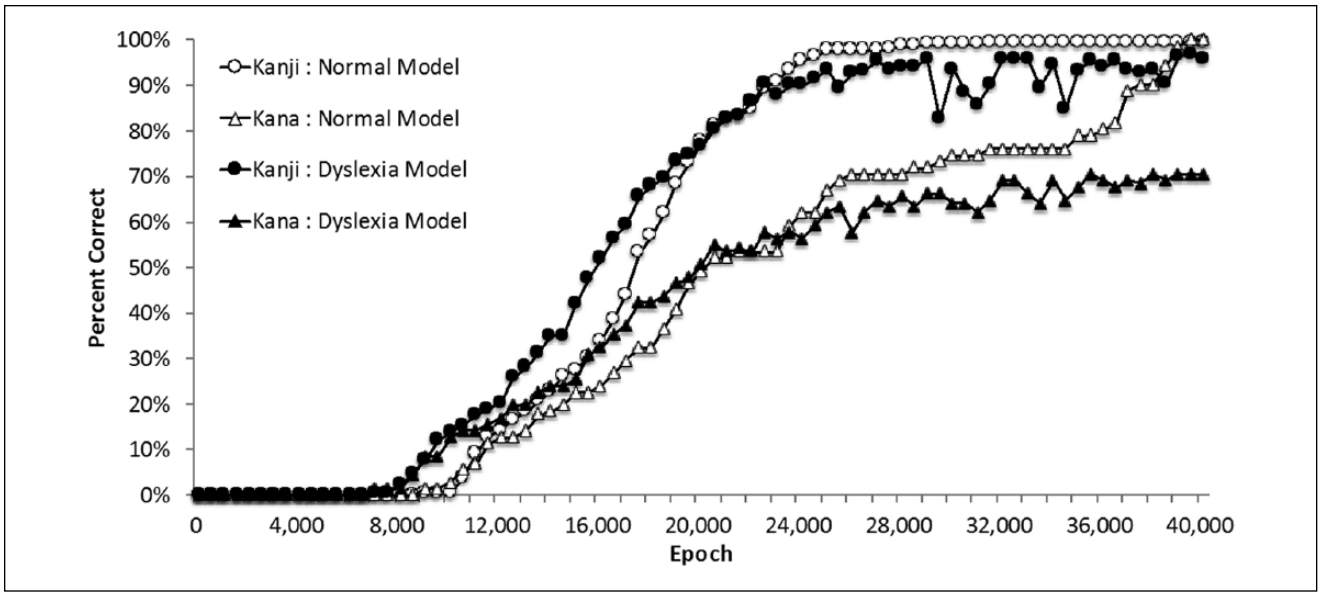

Figure 4. Correct performances of typical normal and dyslexia networks over the course of training.

Table 1. Mean Cycle (Naming Latencies) and Correct Rate of Normal and Dyslexia Networks in Pronouncing Hiragana, Katakana, and Kanji Characters at 40,000 Epochs.

		Hiragana[a]		Katakana[a]		Kanji[b]	
Model	Cycle/Rate	*M*	*SE*	*M*	*SE*	*M*	*SE*
Normal	Cycle	5.51	0.07	5.51	0.07	4.87	0.02
Dyslexia	Cycle	7.17	0.04	7.17	0.04	7.41	0.06
	Correct rate	0.69	0.02	0.69	0.02	0.86	0.02

[a]$n = 71$. [b]$n = 218$.

Table 2. Mean Cycle (Naming Latencies) and Correct Rate of Normal and Dyslexia Networks in Pronouncing Kanji Characters With Three Types of Mora Length at 40,000 Epochs.

		Kanji With Single Mora[a]		Kanji With 2 Morae[b]		Kanji With 3 Morae[c]	
Model	Cycle/Rate	*M*	*SE*	*M*	*SE*	*M*	*SE*
Normal	Cycle	4.68	0.01	4.90	0.02	4.93	0.03
Dyslexia	Cycle	6.69	0.09	7.53	0.06	7.79	0.07
	Correct rate	0.94	0.01	0.86	0.02	0.78	0.03

[a]$n = 37$. [b]$n = 145$. [c]$n = 35$.

as a within-subjects design. There was a significant interaction between model type and script, $F(2, 76) = 190.98$, $p < .001$, as well as significant main effects of model type, $F(1, 38) = 721.49$, $p < .001$, and script, $F(2, 76) = 38.76$, $p < .001$. Within all three types of script, the simple main effects of model type were significant: hiragana, $F(1, 38) = 365.19$, $p < .001$; katakana, $F(1, 38) = 359.23$, $p < .001$; kanji, $F(1, 38) = 1899.79$, $p < .001$. Within each model, the simple main effects of script were also significant: normal model, $F(2, 76) = 200.90$, $p < .001$; dyslexia model, $F(2, 76) = 28.84$, $p < .001$. Post hoc comparisons (Bonferroni's method) revealed that the cycles for both kana stimuli were significantly longer than those of kanji stimuli in the normal model: hiragana versus kanji, $F = 199.34$, $p < .001$; katakana versus kanji, $F = 204.73$, $p < .001$ (hiragana = katakana > kanji). In contrast, the cycles for both kana stimuli were significantly shorter than those of kanji stimuli in the dyslexia model: hiragana versus kanji, $F = 28.46$, $p < .001$; katakana versus kanji, $F = 29.54$, $p < .001$ (hiragana = katakana < kanji).

The accuracy data for the dyslexia model were submitted to a one-way ANOVA, the variable of which was script type: hiragana, katakana, and kanji. There was a significant main effect of script type, $F(2, 38) = 162.84$, $p < .001$. Bonferroni's post hoc comparisons revealed that the accuracy for kanji stimuli were significantly higher than those of both kana stimuli ($MSE = .017$, $p < .001$), but there were no differences between hiragana and katakana stimuli.

Table 2 showed the performances of kanji by mora length. The cycles were also submitted to a 2 × 3 ANOVA with model type (normal and dyslexia) as a between-subjects and mora length (single, two, and three) as a within-subjects design. (Note that the single kanji stimuli with four morae were excluded from the analysis.)

There was a significant interaction between model type and mora length, $F(2, 76) = 65.09$, $p < .001$, as well as significant main effects of model type, $F(1, 38) = 1546.27$, $p < .001$, and mora length, $F(2, 76) = 169.74$, $p < .001$. Within all three types of mora length, the simple main effects of model

type were significant: single mora, $F(1, 38) = 503.72$, $p < .001$; two morae, $F(1, 38) = 1866.77$, $p < .001$; three morae, $F(1, 38) = 1273.16$, $p < .001$. Within each model, the simple main effects of mora length were also significant: normal model, $F(2, 76) = 12.41$, $p < .001$; dyslexia model, $F(2, 76) = 222.43$, $p < .001$. Bonferroni's post hoc comparisons revealed that the cycles for single-mora Kanji stimuli were significantly faster than for two- or three-morae kanji stimuli in the normal model: single mora versus two morae, $F(1, 38) = 16.29$, $p < .001$; single mora versus three morae, $F(1, 38) = 14.05$, $p < .001$, but there were no differences between kanji with two- and three-morae stimuli (kanji: single mora < two morae = three morae for normal). In contrast, in the dyslexia model, the fewer morae that characters have, the shorter the cycles (RTs): single-mora versus two morae, $F(1, 38) = 250.44$, $p < .001$; single morae versus three morae, $F(1, 38) = 268.08$, $p < .001$; two morae versus three morae, $F(1, 38) = 43.73$, $p < .001$ (kanji: single mora < two morae < three morae for dyslexia).

The accuracy data from the dyslexia model were submitted to a one-way ANOVA with the mora length (single, two, and three) as the independent variable. There was a significant main effect of mora length, $F(2, 38) = 55.80$, $p < .001$. Bonferroni's post hoc comparisons revealed that among kanji characters, the fewer morae that characters have, the better the accuracy (single mora versus two morae, $MSE = .021$, $p < .001$; single mora versus three morae, $MSE = .027$, $p < .001$; two morae versus three morae, $MSE = .016$, $p < .001$).

Discussion

In the current study, a connectionist simulation model of reading in Japanese syllabic kana and morphographic kanji was developed in order to verify the validity of the granularity dimension of the HGT postulated by Wydell and Butterworth (1999). The results revealed that both the normal model and the phonological dyslexia model showed a better reading performance on kanji than on kana. In the normal model, the reading cycle for kanji was faster than that for kana, while in the dyslexia model, kanji had a higher reading accuracy than kana, but the reading cycle for correctly pronounced kanji was longer than that for kana, thus showing speed–accuracy trade-off.

In this simulation, one of the unique distinctive features for discriminating kanji from kana was the number of morae. The results showed a better performance for characters having more than one mora, that is, having a bigger granular size, thus providing evidence to support the granularity dimension of the HGT. That is, kanji characters with two or three morae produced more effective processing on the phonological component than kana. This is because kanji have richer representations in terms of the number of active units in the phonological output layer. Even for a unit having a weak activation level, the unit for kanji may be able to recover by recursive input from other units in the attractor network. The more units that are active, regardless of the level of activation, the higher the possibility for recovery, which is in fact in accordance with Jones's (1985) and Plaut and Shallice's (1993) studies. It is for this reason that kanji characters exhibited a better performance than kana. In the current simulation, the granular size was represented by the number of morae per character, and hence the more morae a character had, the higher the performance was.

When the mora length effects in kanji were examined closely, however, the performance of the normal and dyslexia models was contrary to what the HGT had expected: The performance of the dyslexia network on the cycles and accuracy both declined with increasing numbers of morae. Following the HGT, the performance of kanji should have been more robust to lesions to the phonological component. Why then did the results show an opposite trend? A clue to resolve this may lie in a modeling study pertaining to acquired deep dyslexia—a left-hemisphere-damaged neurological patient's reading impairment characterized by a total loss of sublexical reading skills with limited lexical reading skills, that is, reading only via semantics is available (Plaut & Shallice, 1993). These patients' reading errors typically include semantic, visual, and visual-semantic errors as well as inability to read function words/nonwords. Plaut and Shallice's (1993) model of acquired deep dyslexia showed that the model's performance on reading concrete words with more semantic features was worse than that on abstract words with fewer semantic features, under conditions of larger lesions to the semantic cleanup component.

Similarly, as kanji with more morae have greater numbers of active units, they are more effective at engaging in the phonological component. In contrast, kanji with a single mora, which activate only one unit, rely more heavily on the pathway of orthography to phonology (through the intermediary of hidden units) than on the phonological component. As a consequence, kanji with more morae are more likely to be read slowly and produce more reading errors with the network that has lesions to the phonological component.

In the normal model, it was hard for the HGT to explain that the reading cycles for kanji with a single mora were faster than those of kanji with more morae. Further, the reading cycles for kanji with a single mora were faster than those for both types of kana. This is at odds with the HGT, as there should be no differences in reading performance across different scripts. In this case, both a kana and kanji character has the same poor representation, with just one unit being active and with the rest of the 70 units being inactive in the phonological output layer. The kanji reading cycle advantage over kana can be explained by mora frequency, which represents the number of times a target mora appears in the current training corpus (both in the

phonological task and reading task). It is possible that kanji with a single mora have a higher mora frequency than kana.

In order to examine this possibility further, we compared the reading cycles of kanji with a single mora and those of kana with the same mora in the simulation corpus. The normal reading model revealed that the reading cycles for kana were nearly equal to those for kanji: hiragana, 4.75; katakana, 4.75; and kanji, 4.68. The developmental phonological dyslexia model showed a similar pattern of data: hiragana, 6.54; katakana, 6.46; and kanji, 6.43, although the reading cycles of the dyslexia model were in general longer than those of the normal model. That is, there are no qualitative differences here. Further analysis thus indicated that even when the granular size is the same between kana and kanji, the mora frequency affected learning processing latencies.

Indeed, the current simulation study provides evidence for supporting the granularity dimension of the HGT when the results of kanji and kana were compared. The granular size affected reading acquisition: The kanji with larger granularity were faster to learn to read and more robust against lesion than kana with smaller granularity. When considering the effect of mora length in kanji, however, the results were contrary to the predictions of the HGT. Especially in the lesioned model, the larger granular size kanji had, the lower the accuracy and the slower the reading cycle became. These results suggested that the performance of the model was determined not only by the granular size but also by other factors, such as the mora frequency in the training corpus, which has not been discussed in the HGT by Wydell and Butterworth (1999). Only a simulation model like the current model can give further insight into what other words' characteristics may affect reading performance. This needs further and future research with normal and dyslexic readers as participants.

A critique to computer simulation models in general and to the current model in particular, however, might be that the current model is unrealistic, because in order to consider the granularity dimension of the HGT, the whole reading system was simplified, ignoring some other characteristics of kanji characters. For example, (a) unlike kana, kanji characters have meanings, and (b) kanji characters are visually more complex, with a larger number of strokes than kana. Note, however, that opacity of the print-to-sound translation was controlled in this simulation model. These issues need to be considered carefully in future research.

Conclusion

In the current study, a computer simulation model of reading in Japanese syllabic hiragana/katakana and in morphographic kanji was implemented for the first time in order to verify the validity of the HGT (Wydell & Butterworth, 1999), in particular, the granularity dimension. The implementation of the model was successful in this respect when kanji and kana were compared. The study has also identified some limitations to the current simulation model; in particular, some of the characteristics of kanji need to be addressed in a future implementation of a simulation model.

Note

1. Hiragana is underlined in order to differentiate a kanji character from hiragana characters when a verb, adjective, or adverb is written in a combination of a kanji character and hiragana characters.

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