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Division of Labor between Semantics and Phonology in Normal and Disordered Reading Development across Languages

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Abstract

In order to study how statistical patterns in different languages can shape the division of labor in the reading system, we trained two models with the same basic architecture and learning parameters: One was trained to read Chinese, the other English. In Simulation 1, we examined the role of semantics in the early development of reading by comparing results from training with and without input from semantics. Semantic input had relatively modest effects for learning to read English, mainly improving performance on exception words. In Chinese, the influence of semantics was much greater and much more widespread: all types of words were learned more quickly, although the benefit was still greater for words with atypical spelling-to-sound correspondences. In Simulation 2, we simulate the effect of developmental deficits in phonological and semantic processing on the development of reading. Consistent with data concerning individual differences in reading skill, phonological deficits had a much greater impact on English, whereas semantic deficits had a more serious impact on learning to read Chinese. The results demonstrate that differences in the division of labor among readers of different writing systems can be explained in terms of the statistical properties of the writing systems and their interaction with generic associative learning mechanisms.

Keywords: Reading; development; computational modeling

In previous studies, we have examined how a modeling framework developed to explain a variety of phenomena in the translation from spelling to sound in English could be extended to explain similar phenomena in Chinese. Those studies demonstrated that the same basic architecture and learning rules appropriate to English could model the acquisition and use of reading skill in Chinese, and simulate both effects that are directly analogous to English (consistency) and effects that are specific to Chinese (phonetic radical regularity) (Yang, Zevin, Shu, McCandliss& Li, 2006). In the current study, we pursue this further by asking whether two models with the same functional architecture (aside from language-specific orthographic and phonological representations) can capture differences between the two languages in the division of labor between direct and semantically-mediated translation from spelling to sound.

Chinese and English differ in the relative statistical regularity of spelling-to-sound mappings. The distinction comprises differences in both the *grain size* (Ziegler & Goswami, 2006) and *degree of arbitrariness* of mappings between the writing systems. In English, *sub-syllabic* mappings from spelling to sound are dominant, with multiple grain sizes, including single letters, cluster of letters corresponding to single phonemes (graphemes) and larger units (e.g., rimes) contributing to spelling-to-sound mappings, sometimes in conflicting ways. For Chinese characters, in contrast, the mapping from spelling to sound is syllable-based, such that the pronunciation of a whole character is probabilistically determined by its phonetic component. This difference in grain size drives a difference in the *degree of arbitrariness* between the two writing systems: In English spelling, even a very strange word such as YACHT has some predictability (i.e. the Y, A, and T is assigned pronunciations common in other contexts). In Chinese, however, the space of possible pronunciations given an unfamiliar character is unconstrained.

Differences in the statistical regularity of writing systems have important consequences for the development of reading skill. One is a marked difference in speed of learning to read across languages: There is strong evidence that learning to read a regular alphabetic orthography is easier than learning to read irregular orthographies (Seymour, Aro, & Erskine, 2003). The average English child can read 3000-5000 words after first grade (White, Grave& Slater, 1990) whereas Chinese children after first grade can typically read only 667 characters (Xing, Shu, Li, 2004).

A second consequence of orthographic depth on reading development concerns the division of labor between direct- and semantically-mediated spelling-to-sound (Harm & Seidenberg, 2004), i.e., the differential impact of semantics on word reading across writing systems. In a "shallow" orthography, pronunciations can easily be computed directly from spelling, resulting in a relatively limited role for semantics in reading aloud (Raman & Baluch, 2001). In relatively "deep" languages, such as English, semantic knowledge plays a role, particularly in the reading of words whose spellings are highly atypical (Strain, Patterson, & Seidenberg, 1995). Because Chinese is deeper still than English, the role of semantic processing in reading aloud is greater and much more widespread, with the result that the contribution of semantics to the development of Chinese reading is particularly important.

Over the course of development, this difference in the division of labor means that distinct pre-literate language skills will contribute differentially to reading success across writing systems. The relative contribution of "phonological awareness" -- i.e., the ability to categorize and manipulate

individual speech sounds -- and "morphological awareness," – the ability to process the meanings of words as componential – depends on orthographic depth. For example, in transparent scripts such as Arabic, only phonological awareness predicts word reading (Saiegh-Haddad & Geva, 2007). Morphological awareness has only a weak influence on reading in shallower orthographies (McBride-Chang et al., 2005). In Chinese, however, morphological awareness is a much stronger predictor of reading success (Shu, McBride-Chang, Wu, & Liu, 2006), although phonological awareness also appears to play some role (Shu, Peng& McBride-Chang, 2008).

The differential contribution of meta-linguistic awareness measures may indicate specific contributions from more basic cognitive processes to reading, which would help account for the different patterns of reading disorder observed across languages. Developmental dyslexics in shallow orthographies tend to present with slow reading, comprehension difficulties and particular difficulty reading non-words (Lindgren, Renzi, & Richman, 1985). In deeper orthographies, such as English, there is some evidence for subtypes of developmental dyslexia: "phonological dyslexics" who have specific difficulty with decoding and "surface dyslexics" who have specific difficulty with atypically spelled words, but relatively spared performance on regular words and non-words (Manis, Seidenberg et al., 1996). These subtypes are often explained as resulting from distinct pre-existing deficits: in semantic processing for the developmental delay/surface dyslexics and phonological processing for the phonological dyslexics.

In English, children with developmental surface dyslexia are remarkably similar to reading-level matched controls (Manis et al., 1996). Their specific difficulty reading words with unusual spelling to sound correspondences, may be associated with semantic deficits (Plaut, McClelland, Seidenberg, & Patterson, 1996). In Chinese, the influence of semantic deficits is much more serious: Poor semantic processing leads to difficulties with all words, even those with more typical spelling to sound correspondences, although reading of atypically spelled words does suffer relatively more (Shu, Meng, Chen, Luan, & Cao, 2005).

In contrast, developmental phonological dyslexia is associated with deficits in phonological processing. In English, phonological dyslexics present with a reading impairment that is most pronounced for non-words, but, in milder cases, can leave exception word reading more or less intact (Castles & Coltheart, 1993). In Chinese, the pattern is again quite different: Children with phonological deficits are impaired relative to age-matched controls on reading of all words, but the impairment is greater for words with *typical* spelling-to-sound correspondences, with the result that phonological dyslexics do not show the typical advantage for regular-consistent over irregular-inconsistent words (Shu, et al., 2005).

Thus, in both typical and disordered development, the division of labor between phonological and semantic processing in reading differs sharply between English and Chinese. Broadly speaking, phonological processing is more critical for English, and semantic processing is more critical for Chinese. This is likely driven by differences in the computational demands of the two languages. Whereas alphabetic scripts place a premium on skills related to the direct translation from spelling to sound at the sub-syllabic level, logographic scripts embody a much coarser-grained and more arbitrary set of spelling-to-sound mappings. The current simulations explore how these differences in the properties of writing systems can drive developmental differences in the organization of the reading system, given the same basic functional architecture.

Simulation 1: the Role of Semantics in Normal Reading

Architecture

The same basic architecture was used for two models: One for Chinese and one for English. Each model had an orthographic input layer designed to represent the spellings of words in each writing system, fully connected to a hidden layer of 100 hidden units, which was in turn fully connected to a phonological output layer designed to represent the pronunciations of words in that language. The phonological output layer was fully connected both directly to itself and to 50 "cleanup" units, permitting the formation of attractor states, following Harm & Seidenberg (1999).

The English representations of orthography and phonology were adapted from the scheme of Harm & Seidenberg (2004): 101 units were used to represent 10 slots of letters in the orthographic layer and 200 units were used for 8 slots to represent phonemes in phonological layer. The Chinese orthographic representation consisted of 270 units based on a linguistic description of Chinese orthography including radicals, number of strokes and radical position (Xing et al., 2004; Yang et al., 2006). 92 units were used to code each Chinese syllable, which includes five slots: one onset slot, three rime slots, and a fifth slot for tone.

A semantic input layer was also included; semantic patterns were random-bit sequences designed to capture only the most abstract characteristics of word meanings (Plaut, 1997). 3000 semantic exemplars clustered into 120 categories over 200 semantic features were created and 2881 patterns were assigned randomly to the words in English training corpus. A subset of 2689 patterns from the English training patterns were selected and randomly assigned to Chinese characters. While this has the disadvantage of not providing a realistic representation of the similarity of the meanings of words within a language, it has the advantage of permitting us to use the same semantic patterns for both languages, thus allowing a direct investigation of the role of spelling-to-sound granularity and arbitrariness on the division of labor. The semantic input layer was connected to the output layer via 100 hidden units. For each language, the model was run 10 times with no semantic input (hereafter, the orthography to phonology or OP simulation) and 3 times

with the semantic input included (hereafter the orthography/semantics to phonology or OSP simulation). Each run of the model used a different random seed; results are reported from the averages of all runs.
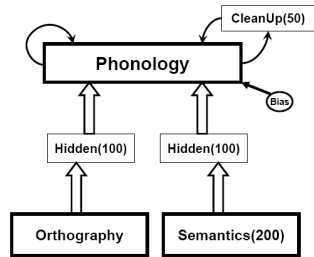

Figure 1: Model architecture

Training

Following Harm & Seidenberg (1999), we first pre-trained the phonological attractor net to an error threshold of 0.01), and the final weights (120K in Chinese and 300K in English model) of phonological attractor net were embedded in the reading model. To avoid "catastrophic interference", interleaved training (Hetherington & Seidenberg, 1989) on phonological and reading was adopted. Training mixed 10% "listening" trials, on which only the phonological attractor was trained, with 90% "reading" trials, on which the whole model was trained. A learning rate of 0.005 and momentum of 0.9 were used. Online learning was used with the continuous recurrent back-propagation algorithm (Pearlmutter, 1995). Each word was selected according to the training probability transformed via square root compression.

The Chinese training corpus of 2689 characters consisted of 2390 characters from a set of naming norms (Liu, Shu, & Li, 2007) and plus 299 additional items from phonetic families represented in the testing materials. Frequency estimates was taken from the Modern Chinese Frequency Dictionary (Wang, 1986). The English training corpus consisted of 2,881 monosyllabic words assigned frequencies taken from the Marcus, Santorini, and Marcinkiewicz (1993) norms, which are based on 43 million tokens from the *Wall Street Journal.*

Testing

Naming accuracy and sum squared error (SSE) were computed to test the model's performance. Accuracy was determined by applying a winner-take-all scoring system: for each slot on the output layer, we determined which phoneme was closest to the pattern on the output at the final time tick and reported this as the model's pronunciation. SSE, a stand-in for response latency, was computed from the model's output at the 11th time tick by adding together the square of the difference between the model's phonological output for each unit and the target output.

Results

Following Harm & Seidenberg (1999), the English model was tested after 1.5M trials. The Chinese model was tested at 2.5M trials to match overall accuracy. Training without semantic (OP) input resulted in a high level of accuracy on the trained items for both languages (98% in English, 89% in Chinese).

To investigate whether the same architecture could provide an account of basic phenomena in adult reading for both languages, we tested the frequency by consistency interaction using benchmark stimuli from two studies: one of Chinese, the other of English. In both languages, the typical pattern of results reveals interacting effects of regularity/consistency, such that irregular-inconsistent (I-I) words are named more slowly that regular-consistent (RC) words, with a much larger effect of regularity for low-frequency, relative to high-frequency words.

For the English model, 144 monosyllablic words were tested from previous empirical (Taraban & McClelland, 1987) and modeling (Plaut, et al., 1996) research. Overall accuracy was 96.81%. Sum squared error results replicated significant main effects on response latency of frequency, $F_{(1,138)} = 8.09$, Mse=.25, P<.01, and regularity/consistency, $F_{(2,138)} = 3.92$, Mse=.12, P<.05, as well as the interaction between them, $F_{(2,138)} = 2.71$, Mse=.08, P=.07. The regularity/consistency effect was significant only for low frequency items, $F_{(2,139)} = 6.25$, Mse=.20, P<.01, not for high frequency items, F<1.

The Chinese model was tested on 120 characters used in previous modeling and naming experiment (Yang et al., 2006). Overall accuracy was 92.67%. The model replicated main effect of frequency $F_{(1,114)} = 36.63$, Mse=5.91, p<0.01 and of regularity/consistency, $F_{(2,114)} = 3.50$, Mse=0.56, P<0.05 and the interaction between them, F <1. The regularity/consistency effect was significant only for low frequency items $F_{(2,115)} = 5.57$, Mse=1.18, P<0.01, no difference was found for high frequency items, F<1.

The inclusion of semantic input during training had very different effects on learning trajectories between the two languages. As shown in Figure 2, the inclusion of semantic input had a relatively limited impact on learning spelling-to-sound in English, with a modest increase in the speed of acquisition overall (98% for OP and 99% for OSP after 1.5M trials), and a small benefit for irregular/inconsistent (I-I) items (88% for OP and 100% for OSP). In contrast, for Chinese, the inclusion of semantics improved the speed and accuracy of learning for all item types (88% for OP and 99% for OSP after 2.5M trials)**.** There was a large effect of the inclusion of semantic input on performance for I-I items (77% for OP and 100% for OSP), and a somewhat smaller, but significant impact on R-C items (91% for OSP and 100% for OSP).
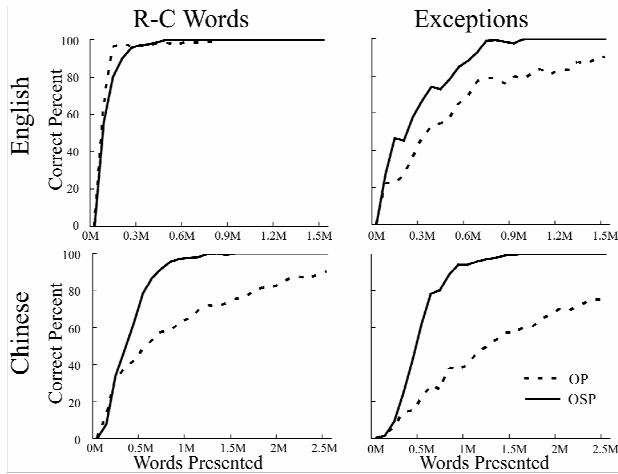
Figure 2: Semantic contributions to regular and exception words across languages

Discussion

The results demonstrate that differences in the role of semantics in learning to read can be simulated as the result of differences in the computational demands of learning to read English and Chinese in the context of the same functional architecture. This provides an account of the differential role of pre-existing skills in phonological and semantic processing in predicting individual differences in typical reading development. Simulation 2 extends this approach to consider the impact of pre-existing deficits in phonological and semantic processing for the two writing systems.

Simulation 2: Developmental Impairments and Division of Labor

Methods

To study differences between languages on the emergence of the phonological dyslexia and surface dyslexia symptoms over the course of literal acquisition, pre-literature deficits in either semantic or phonological processing were simulated in the model using weight decay. Phonological deficits (P-) were simulated by applying weight decay to all connections between the orthographic input and phonological output layer, via the hidden units. Semantic deficits (S-) were simulated with analogous decay on the connections between semantics and phonology. Although there are arguments for implementing phonological deficits as impairment to the output attractor network (Harm & Seidenberg, 1999), this current approach permits us to observe the influence of the same type and intensity of "damage" on each pathway. Three levels of weight decay were used: 1×10^{-4}, 5×10^{-5} and 1×10^{-5}. Aside from the application of weight decay during training on reading trials, architecture and training were identical to the OSP model in Simulation 1. Results are the average from all three levels of decay.

Results

When comparing the impact of phonological and semantic deficits between English and Chinese, clear qualitative differences in the division of labor for disordered reading we observed between the two languages.

The phonological deficit (P-) had a much stronger effect on English reading than Chinese. Non-words reading was severely impaired for English model (after 1.5M trials, accuracy for naming of non-words from Glushko, 1979, Experiment 1, 80% for OSP and 22% for P-), whereas word reading ability was acquired more slowly than the intact English model, and was moderately impaired for regular (83%) and exception words (74%)(See Figure 3). In contrast, although the Chinese P- model learned more slowly than the unimpaired model, it achieved near-perfect word reading accuracy at the end of training (97% for R-C and 90% for exceptions, contrast to 100% for both in OSP).
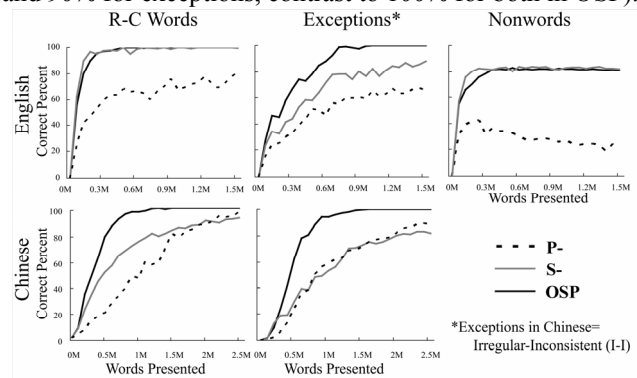

Figure 3: Deficits by language and stimulus type

Introduction of a semantic deficit impaired reading for all words in the Chinese model, with a stronger effect on irregular/inconsistent items than on regular/consistent items (95% for R-C and 83% for I-I in S-, in contrast to 100% for both conditions in OSP). In contrast, the English S- model learned all words somewhat more slowly than the control OSP model, but eventually acquired quite normal performance on R-C items, with a specific impairment on I-I items reflecting a pattern of developmental surface dyslexia.

We now turn to a simulation of three specific cases of developmental dyslexia in Chinese reported by Shu et al. (2005). They reported one case of surface dyslexia associated with specific deficits in morphological awareness tasks and spared performance in phonological awareness tasks. We simulated this child (a 9 year-old boy) by selecting a point in training at which the S- model had similar overall accuracy to the child (approximately 45%), at 440k training trials. At this level of overall performance, the S- model's ability to read words was influenced by stimulus regularity (46.7% accuracy for regular items vs. 26% for irregular, x^2=2.81, P=0.08), which roughly matches the performance of the children with semantic deficits who exhibited symptoms of surface dyslexia on the same items (53% and 37% for regular and exception items, respectively).
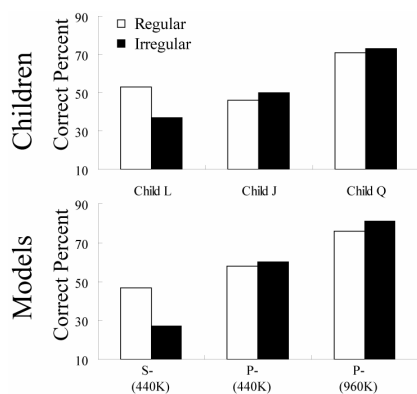
Figure 4 Simulation for cases of children with developmental dyslexia reading Chinese

We used the same matching technique to simulate two cases of developmental phonological dyslexia – children who scored poorly on measures of phonological awareness, but within normal range for morphological awareness. The younger child (J, 10y8m) had equal difficulty with regular (46%) and exception words (50%). After 440K trails of training, when the accuracy of the model matched the child's, it exhibited a similar pattern (58% for regular and 60% for irregular). The older child (Q, 12y2m) also did not show a regularity effect (71% for regular and 73% for irregular), which was simulated by the model (76% for regular and 81% for irregular) trained for 960K trails.

Discussion

Simulation 2 explored the impact of core deficits in phonological and semantic processing for reading in English and Chinese. The model provides insight into how dyslexia can take on different forms in the two languages. In English, mappings from spelling to sound are much more efficient than mappings from spelling to meaning, with the result that deficits that impact the translation from spelling to sound are much more serious than deficits that impact meaning to sound. In Chinese, on the other hand, spelling-to-sound mappings are more arbitrary, resulting in greater reliance on semantic input under normal circumstances, and a much greater impact of semantic deficits on reading aloud in general. Despite these differences, for both languages, the impact of deficits in direct translation from spelling to sound is greater for regular/consistent words and the impact of deficits in meaning-to-sound translation is greater for irregular/inconsistent items.

General Discussion

We presented a series of simulations that apply the same functional architecture and learning rules to reading Chinese and English. This permitted us to investigate how the division of labor (Harm & Seidenberg, 2004) between semantics and phonology is driven by the computational demands of a particular writing system. The simulations provide both a general computational account of how differences in orthographic depth influence reading development, and a novel, specific account of developmental dyslexia in Chinese.

Simulation 1 compared models with and without semantic input to demonstrate that the relatively opaque mapping from spelling to sound in Chinese drives a much stronger reliance on semantics than English. Simulation 2 compared the influence of pre-existing deficits in phonology and semantics between languages, and the pattern of results was generally consistent with cross-linguistic studies of dyslexia: Phonological deficits have a greater influence on reading in English, specifically resulting in poor non-word reading accompanied by general impairment to word reading, whereas semantic deficits result in a deficit essentially limited to exception words. In contrast, for Chinese constitutive deficits in semantic processing had a widespread impact on word reading, which was greater than the influence of phonological deficits.

Finally, we presented simulations of three cases of developmental dyslexia in Chinese. In each simulation, there was independent motivation to implement the core deficit in a particular subsystem. One child had frank difficulties with morphological processing, but relatively normal phonological awareness. His data were simulated by implementing a deficit in the semantics-to-phonology pathway throughout development and matching the model's overall performance to the patient's. Conversely, two other subjects who showed frank phonological awareness difficulties in the absence of morphological processing deficits were simulated by implementing the same type of deficit on the direct mapping from spelling to sound. In both cases, the pattern of reading disability was correctly predicted by the model.

Although the model provides an initial account of the division of labor in two languages, it has some limitations that should be addressed in future studies. One unique aspect of Chinese not simulated here is the fact that spelling-to-meaning correspondences are quasi-regular in the same way that spelling-to-sound correspondences are. Because the current model uses random bit semantics, and simulates semantics as an input representation rather than computing meaning from print, it cannot address this phenomenon and furthermore may be underestimating the role of semantic processing in learning to read Chinese. An important step in future modeling will be the inclusion of more realistic feature-based semantics (although this makes it difficult to match items across languages) and using a full "triangle" architecture with orthography as an input and semantics and phonology as output layers trained in an interleaved fashion (e.g., Harm& Seidenberg, 2004).

Another limitation of the model is the scale of the effect of phonological impairment on English reading. The phonological impairment results in extremely poor non-word performance in English, and also has a much

greater effect on word reading than is typically seen in developmental phonological dyslexia. The influence of phonological deficits on Chinese, while still somewhat smaller than the influence of semantic deficits, is also likely to be overestimated. This may be a result of the decision we made to make the phonological and semantic lesions more equivalent by applying decay to the weights connecting the inputs to the outputs via the hidden layer. Harm & Seidenberg (1999) abandoned this approach to simulating phonological dyslexia on both practical and theoretical grounds. Practically, they observed the same extreme deficits we did on non-word reading. Theoretically, they argued that the deficits observed in phonological dyslexia were more in line with constitutive deficit in the formation of attractors. Future simulations will simulate phonological deficits on the output following Harm & Seidenberg (1999).

Acknowledgement

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