Exploring the relations between oral language and reading instruction in a computational model of reading

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Abstract

To become a proficient reader, children have to learn mappings between print, sound and meaning. There is debate over whether reading instruction should focus on the relations between print and sound, as in phonics, or on the relationship between print and meaning, as in sight word reading. In a study where participants learned a novel artificial orthography, Taylor, Davis and Rastle (2017) compared print to sound focused or print to meaning focused reading training, demonstrating that sound training was superior for learning to read. However, a benefit from sound focused training is likely dependent on prior acquisition of effective sound to meaning relations of words. To explore this issue, we developed a connectionist model of reading. We exposed the model to a sound or a meaning focused training, but varied the model's pre-acquired oral language skills. The simulation results showed that proficiency in oral language is a determinant of the advantage of print to sound focused reading training, suggesting that reading training should address both oral language skills and print to sound mappings.

Keywords: reading instruction; oral language; reading development; computational modelling; word learning.

Introduction

Learning to read requires mastery of a set of complex skills involving encoding phonology (P), semantics (S), and learning to map orthographic (O) forms onto those representations of sound and meaning. Even for alphabetic orthographies, where a letter, or set of letters, corresponds approximately regularly to a phoneme in the word, learning to read is effortful and frequently fraught with difficulties (Seidenberg, 2017). Effective early reading instruction is therefore critical to help children become proficient readers. There has been a vigorous debate over whether reading instruction should focus on the relations between print and sound or on the relationship between print and meaning. The former is typically characterized by phonics-style training, where the phonemes associated with particular letters or letter clusters are trained intensively, enabling children to decode letter-by-letter. The latter is often referred to as meaning-focused or whole-word language instruction, where the meaning and pronunciation of the whole word is provided to the child during training.

Proponents of the phonics method argue that reading instruction should focus on learning spelling-to-sound mappings because exploiting the systematicity of alphabetic writing systems ought to be substantially easier than acquiring more arbitrary spelling-to-meaning mappings, where the arbitrariness of the sign is dominant and learning can only be accomplished word by word, without the benefit of generalising from one learned word to the next. Evidence for the strong predictive relation between phonological decoding skills and reading acquisition (see, e.g., Rayner et al., 2001, for a review) demonstrates that phonological skills are key to reading success.

Alternatively, researchers who advocate the meaning-focused method (see, e.g., Davis, 2013, for a review) argue that the primary goal of reading is to access the meanings of words and so this ought to be the priority of reading training approaches. Although spelling-to-meaning mappings are hard to learn, they may still be acquired early in reading development (Nation, 2009; Taylor et al., 2015). For example, Nation and Cocksey (2009) demonstrated that 7-year-old children could access semantic categories of words from orthography very quickly without evidence that the phonological form of the words mediated responses.

Effectiveness of sound-focused and meaning-focused reading instruction

According to the Simple View of reading (Gough & Tunmer, 1986), reading comprehension is the product of phonological decoding and oral vocabulary. During reading training, learners acquire mappings from print to sound, and access meaning based on their knowledge of sound-to-meaning mappings acquired pre-literacy. There is some evidence that both print to sound mapping skills (as indexed by pseudoword reading tasks) as well as sound to meaning mapping skills (as reflected in oral vocabulary tasks) are predictors of silent reading comprehension performance (e.g., Curtis, 1980; Nation & Snowling, 2004; Ouellette & Beers, 2010; Ricketts, Nation, & Bishop, 2007). However, the Simple View of reading does not consider an alternative, which involves the role of accessing meaning directly from print (Taylor et al., 2015).

Within the connectionist view of reading (Seidenberg & McClelland, 1989; Harm & Seidenberg, 2004; Plaut et al.

1996), learning to acquire the meaning of written forms of words could be via developing direct orthographic to semantic mappings. Alternatively, acquisition could be indirect, through the learner developing orthographic to phonological mappings, which then map, via oral language knowledge, onto semantic representations. Computational modelling investigations have established that there is division of labour along these direct and indirect pathways from orthography to semantics over development (Harm & Seidenberg, 2004; Plaut et al. 1996). However, comparisons between reading training that focuses on developing the direct orthographic-to-semantic, versus the indirect orthographic-to-phonological, pathways have not as yet been undertaken.

One exception to this is a recent study by Taylor, Davis and Rastle (2017). In a laboratory study using adults, Taylor et al. compared reading acquisition when training was biased toward orthography-to-semantics (OS) mappings versus orthography-to-phonology (OP) mappings. They trained literate adult participants to read two sets of 24 novel words which were written in two different unfamiliar alphabetic orthographies (in each orthography, one character related to one phoneme) – see Figure 1. Each novel word was assigned a familiar concrete noun meaning (e.g., /ɡɛd/ referred to camel, and /kɛs/ referred to parsnip), and the mappings between novel words and their referents were counterbalanced across participants).

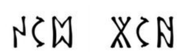

Figure 1. /ɡɛd/ and /kɛs/ in the artificial orthography from Taylor et al. (2017).

Prior to reading training, participants were exposed to the mappings between phonology and semantics for the novel words. Then, participants learned orthographic-to-phonological and orthographic-to-semantic mappings for both orthographies. For one orthography, participants received OP focused training, which involved three times as many orthographic-to-phonological training trials as orthographic-to-semantic training trials, whereas for the other orthography they received OS focused training, which involved three times as many orthographic-to-semantic as orthographic-to-phonological training trials. The results demonstrated that OP focused training led to better accuracy and speed in reading aloud, and it also had a transferable benefit to reading comprehension. By contrast, OS focused training resulted in faster but not more accurate reading comprehension, and showed no transferable benefit for the reading aloud task.

Taylor et al. (2017) demonstrated that both reading aloud and reading comprehension accuracy could be promoted by focusing on OP mappings during reading training. However, unlike children learning to read for the first time, participants were acquiring an orthography which very likely piggy-backs on the reading system that the participants already have. Thus, an outstanding question is the extent to which prior language skills, particularly between phonology and semantics, are critical to the OP versus OS focused reading training differences.

Furthermore, a key aspect of Taylor et al.'s (2017) study design was that participants were pre-trained on mappings between phonological and semantic forms for the novel words. This previously tuned phonology-semantics system is crucial to allow the transference of knowledge from training on OP mappings to access meaning from print, since this requires using not only the OP but also the PS routes within the reading system.

According to the connectionist view of reading, then, phonics instruction will be most successful if the participant has acquired an effective level of oral language knowledge. Thus, in relating the laboratory-based studies of reading acquisition to the child's task of learning to read, the relative contribution of training from OP and OS on reading acquisition needs to be considered alongside the contribution of pre-literate oral language skills.

Computational models of reading

Computational models of reading have converged on an architecture involving two different pathways that are active during reading – a subword orthographic to phonological pathway and an orthographic whole word pathway, which may map onto a whole-word phonological representation and/or a semantic representation of the word (Coltheart et al. 2001; Plaut et al. 1996). There are also mappings between phonological and semantic representations, meaning that words can be comprehended both by direct OS mappings, and also indirectly via OP then PS mappings. In the connectionist tradition, the relative contribution for generating phonology or semantics via different reading pathways is flexible, and can be determined by properties of individual words, such as high-frequency words more likely to be read via direct OS mappings, or due to properties of the orthographic system itself, such as ideographic writing systems more likely to utilize the direct OS mappings than alphabetic writing systems (Chang, Welbourne & Lee, 2016; Harm & Seidenberg, 2004; Plaut et al. 1996).

In this study, we implemented the two reading schemes tested in Taylor et al.'s (2017) study, in order to determine whether the connectionist triangle model of reading is able to replicate the behavioural effects of an OP focused versus an OS focused training regime. Furthermore, we examined whether the advantage for the OP focused training demonstrated in Taylor et al.'s (2017) study was present even for the model with poor oral language skills, or only when well-established mappings between phonological and semantic representations were in place. Tracking the relative benefit of OP and OS focused training according to pre-literate oral language skills enables greater clarity on how different reading training schemes may benefit readers with varying language abilities.

Following Harm and Seidenberg (2004), we developed a fully implemented connectionist model of learning to read, that mapped between representations of orthography, phonology, and semantics of words. The model was pretrained to different degrees of proficiency in mapping between phonological and semantic representations of words, to simulate pre-literate oral language skills. We tested three different quantities of pre-training to reflect a model with moderate, medium, and high levels of oral language skills, in terms of the overall fidelity of phonological and semantic representations within the model, and the proportion of words in the language for which the model was able to generate the correct semantic and phonological representations. We then compared the effects of two reading training regimes with different focuses of reading instruction – *orthography to phonology (OP) focused model* or *orthography to semantics (OS) focused model*. Prior to learning to read, both models received three different amounts of pretraining (i.e. 500, 1000, or 2000 epochs) on mappings between semantics and phonology. The OP focused model then received three times as much training on the OP mappings, while the OS focused model received three times as much training on the OS mappings. We evaluated the model's performance under these different training regimes using tasks of reading aloud and reading comprehension.

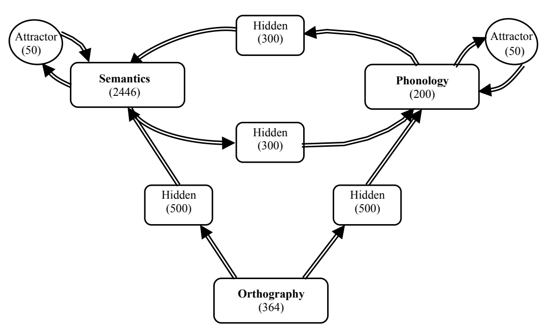

Figure 2. The architecture of the developmental model of reading.

Method

Network Architecture

The architecture of the model is shown in Figure 2, which was the same as the developmental model of reading implemented in Monaghan, Chang, Welbourne, and Brysbaert et al. (2017) and Chang, Monaghan, and Welbourne (2016). The model consisted of three key processing layers representing orthographic, phonological and semantic representations respectively, and four hidden layers that learned to map between the processing layers. An attractor layer, which contained 50 hidden units, was connected to and from the phonological layers. Similarly, there was a set of 50 hidden units for the semantic layer. The use of attractors was to help the model to develop stable phonological and semantic representations of words. The semantic layer was connected to the phonological layer through a set of 300 hidden units, and the phonological layer was connected back to the semantic layer through another set of 300 hidden units. The orthographic layer was connected to both the phonological and semantic layers through different sets of 500 hidden units.

Training Corpus: Artificial Words

The training corpus comprised 24 artificial words, taken from the materials in Taylor et al. (2017). For the phonological forms, all items were monosyllabic consonant-vowel-consonant pseudowords. All items were constructed from 12 consonants (/m/, /t/, /g/, /b/, /k/, /d/, /n/, /s/, /z/, /v/, /p/, and, /f/) and four vowel phonemes (/ɛ/, /I/, /ɔ/, and, /ʌ/). For phonology, each word was represented in the 3^{rd}, 4^{th} and 5^{th} slots of a set of eight phoneme slots, with each slot consisting of 25 phonological features. Each word was thus positioned with its vowel at the fourth phoneme slot. The first three slots were for onset consonants, and the last four slots were for coda consonants, but because all words in the set had one onset and one coda consonant, only one of these slots was used during training (so for the word "*tep*" its phonology was represented as _ _ t ɛ p _ _ _, where _ indicates an empty slot). For orthographic forms, the correspondence between letters and phonemes was transparent (i.e., there was a one-to-one correspondence). For orthography, each word was represented across a layer containing 14 letter slots with each slot comprising 26 units, each of which could represent a distinct letter, so an alphabet up to 26 letters could be represented. Words were positioned with their vowel aligned on the fifth slot. Consonants preceding the vowel were positioned in slots right before the vowel and consonants following the vowel were positioned starting from the seventh slot. This representation was in alignment with Chang et al. (2016), which enabled words up to 14 letters to be represented. However, because all words were three letters in length, with one onset and one coda consonant, words occupied only the 4^{th}, 5^{th}, and 7^{th} slots (so for the word "*tep*" its orthography was represented as _ _ _ t e _ p _ _ _ _ _ _ _). Note that we use here Roman alphabet as a short hand to reflect the alphabet used in the laboratory-based study. There is nothing particular in the representations used in the model regarding the particular alphabet used, only that the model is able to distinguish the letters from one another from the outset, but does not know the properties of the letters in other respects in advance of commencing training.

For semantics, a set of familiar objects consisting of six fruits and vegetables, six vehicles, six animals, and six tools were randomly assigned to the 24 artificial words. The semantic representation for each word was derived from Wordnet (Miller, 1990), following Harm and Seidenberg (2004). Each semantic representation was composed of 2446 semantic features. The presence of semantic features was encoded as 1 and the absence of semantic features was encoded as 0 in the respective slot.

Training Procedure

The model was trained on the 24 artificial words. All the training parameters were exactly the same as those used in our previous modelling work (Chang et al., 2016). The training process had two phases: pretraining and reading training. For the pretraining, the model learned to map from phonological to semantic (PS) representations in an oral vocabulary task and from semantic to phonological (SP) representations in a meaning naming task (e.g. picture naming). To investigate how oral language skills affected literacy development, three different amounts of pretraining were used – 500, 1000, or 2000 learning trials. For the oral vocabulary (PS) task, the phonological representation of the word was clamped at the phonological layer for eight time steps, and the model generated a semantic representation at the semantic layer. The difference between the actual and the target semantic representation was then calculated, and the weights on connections between all the layers were adjusted according to gradient descent backpropagation through time in order to reduce the error. The training rate was 0.1. Similarly, for the meaning naming task (SP), the semantic representation was clamped at the semantic layer for eight time steps, and the model was required to produce a phonological representation. In pretraining, the model additionally learned to develop a stable phonological attractor (PP), and a stable semantic attractor (SS), by presenting the phonological or the semantic representation for two time steps, then allowing the model to cycle activation for a further six time steps to reproduce the initial representation. During pretraining, these four tasks (PS, SP, PP, and SS) were interleaved, with 40% of trials for the oral vocabulary task, 40% of trials for the meaning naming task, 10% of trials for the phonological attractor and 10% for the semantic attractor. For each trial, a word was randomly selected.

After pretraining, the weights on connections between the semantics and the phonology layers were frozen. The model was then trained to learn to read with different focuses of reading instruction, in two separate simulations as either the OP focused or OS focused model. For the OP focused model, there were three OP trials for every OS trial, and for the OS focused model the reverse was true. For an OP trial, the model's error at the phonological layer at the final time step was computed and then backpropagation with gradient descent adjusted the weights to reduce this error. For an OS trial, error was propagated from the semantic representation. Each model was trained for 1000 reading trials. For each reading learning trial, a word was randomly selected and presented at the orthographic layer for 12 time steps. Five versions of each model were trained with different random initial weights and different random samplings from the words.

Testing Procedure

For testing the model's phonological output, we determined the number of words for which all phonemes were correctly produced. The closest phoneme representation from the set of all phonemes in the language was derived from the model's actual production and this was then compared against the target phoneme. If the actual and target phonemes were the same, then the model was judged to have spoken the word correctly. For testing the model's semantic output, the activation of units at the semantic layer was recorded. Accuracy was measured by computing the Euclidean distance between the model's actual semantic representation and the semantic representation of each word in the training corpus. If the smallest distance was for the target representation then the model was judged to be correct. We examined how the different training focuses affected reading performance at various stages during training.

Results

Network Performance

For the pretraining tasks, the model that was trained with 500, 1000, and 2000 presentations achieved 74%, 89.6%, and 100% accuracy on the meaning naming (PS) task and 41.7%, 80.2% and 97.9% accuracy on the oral vocabulary (PS) task, respectively. This pattern of results is in line with performance of the model when trained with a substantially larger vocabulary (Monaghan et al., 2017). The three training schedules thus reflect different levels of pre-literate oral language skills, from poorer through to near-perfect vocabulary knowledge.

Figure 3 shows the average performance of the OP and OS focused models with the different amounts of pretraining at different stages of reading training. We analysed the model's performance by using generalized linear mixed effects models with accuracies in reading aloud or reading comprehension as the dependent variable, depending on the task. Item and simulation (simulations one to five) were included as random factors, and training focus (OP or OS), reading time (epoch 100 to 1000) and pretraining (500, 1000, or 2000) were included as fixed factors.

Overall, the model performed better on the tasks for which it had undergone intensive training. For reading aloud, the OP focused model performed better than the OS focused model. Adding training focus as a fixed factor resulted in a significant improvement in model fit compared to a model with random effects of item and simulation and with fixed effects of reading time and pretraining, $\chi(1) = 398.86$, $p < .001$. For reading comprehension, the OS focused model performed better than the OP focused models, as again indexed by the fact that adding training focus improved model fit, $\chi(1) = 314.25$, $p < .001$.

However, the effect of pretraining had an asymmetric effect on the reading aloud and reading comprehension tasks, according to whether the model had been trained with OP or OS focus. For reading aloud, the effect of different levels of pretraining, reflecting oral language skills, had a null effect on performance for both the OP and the OS focused models. Adding pretraining as a fixed factor did not result in a significant improvement in model fit compared to a model with random effects of item and simulation and with fixed effects of reading time and training focus, $p > .05$. Note that the trajectories of the lines for the OS focused model for 500 and for 2000 pretraining trials are very close together, as they are for the OP focused model. In contrast for reading comprehension, the effect of pretraining had a substantial effect on the OP training focused model - adding pretraining as a fixed factor improved model fit compared to a model with random effects of item and simulation and with fixed effects of reading time and training focus, $\chi(2) = 34.42$, $p < .001$. Specifically, after substantial pretraining (2000 pretraining trials, producing close to 100% in oral vocabulary and meaning naming tasks), the performance of the OP focused model began to converge with that of the OS focused model. The beneficial effect of the OP training focus is strongest for the model with advanced oral skills prior to literacy onset. This observation was confirmed by the fact that adding the interaction between pretraining and training focus as a fixed factor improved model fit compared to the model containing random and fixed effects, $\chi(2) = 9.86$, $p < .001$. Looking at each level of pretraining, the difference between the OP focused model and the OS focused model was the smallest for 2000 pretraining trials, $\beta = 1.47$, followed by 1000 pretraining trials, $\beta = 1.81$, and then 500 pretraining trials, $\beta = 2.01$.

These results for the skilled oral language model are in tune with the behavioural results from Taylor et al. (2017). Figure 3 (right) shows the performance of the participants trained with the OP versus OS focus languages on each day taken from Taylor et al.'s figures 3 and 4. Similar to the behavioural data, the performance of the OP and OS focused models converged after substantial training and this is likely due to the fact that the training sample was relatively small.

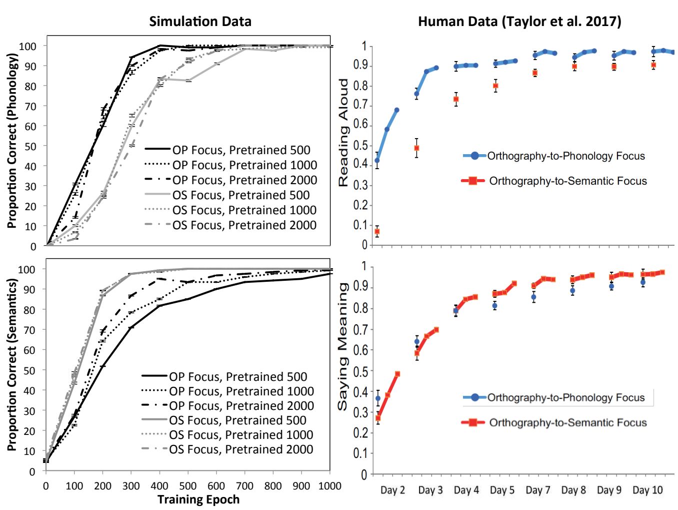

Figure 3. The performance of the OP and OS focused models with different amounts of pretraining over the time course of the reading training (Left). The performance of the participants trained with the OP and OS focus languages on each day from Taylor et al. (2017, right). The error bars indicate ±SEM.

Discussion

We developed a fully implemented connectionist model of reading that mapped between orthography, phonology, and semantics and explored the influence of oral language on the effectiveness of different types of reading instruction. The laboratory study on which this work was based indicated that focusing on learning mappings between print and sound also transferred to promote mapping between print and meaning, whereas focusing on learning print to meaning mappings resulted in deficiencies in learning print to sound and had little advantage for mapping from print to meaning. The consequences of this, if they extend to children's learning, are that, given limited instructional time, learning should focus on phonics, rather than on meaning-based strategies for reading acquisition.

Our model replicated these effects: a model which focused on print to meaning (i.e., OS training focused model) had deficiencies in learning to map from print to sound, whereas a model which focused on print to sound (i.e., OP training focused model) was better at learning reading aloud tasks, and converged in performance for reading comprehension tasks with the OS training focused model which had three times as much experience of comprehension trials during training.

However, importantly this convergence was dependent upon the model's preliteracy training. Only when the model had high accuracy in its mappings between phonology and semantics was it able to transfer performance from OP training trials to perform well on reading comprehension. This pattern of performance from the OP training focused model with high oral language skills was similar to the behavioural data reported in Taylor et al. (2017). Our computational results demonstrate that the advantage of OP focused training only pertains in cases where good oral language skills are present. This is because the transfer from OP training trials to OS task performance requires effective mappings from phonology to semantics. If these are not present then the effective learning of OP mappings in the model stops just there – any high fidelity representation of phonology cannot then accurately activate the target semantic representation. OP training, then, is only advantageous for reading comprehension when the learner has good oral language knowledge, consistent with the view that addresses the role of oral language in reading (Gough & Tunmer, 1986; Harm & Seidenberg, 2004; Plaut et al. 1996).

The results are thus far compatible with empirical evidence of the benefit of both print to sound decoding skills and oral language skills on reading ability (e.g. Curtis, 1980; Nation & Snowling, 2004; Ouellette & Beers, 2010; Ricketts, Nation, & Bishop, 2007), which relate to the two segments of the indirect route from orthography to semantics via phonology. Further investigation of the model's performance will enable us to determine whether this is the way in which the model functions to solve the mapping tasks. We suggest that, for reading aloud, the direct OP pathway is likely to be most effective for performing the task regardless of the training focus, because the systematic mappings are easier to learn compared to the indirect OSP pathway which requires two arbitrary mappings. Thus, more training of the direct OP pathway is likely to be beneficial. In contrast, for reading comprehension, the indirect OPS pathway may again be more effectively used, because it exploits a regular OP mapping and a previously learned arbitrary PS mapping, whereas the direct OS pathway is arbitrary and needs to be acquired. We might then expect the indirect pathway to have a substantial contribution to reading comprehension performance for both OP and OS focused training, in the context of highly accurate PS mappings.

Previous studies have showed that the division of labour between the phonological and semantic pathways in connectionist models of reading could be shaped by word properties or orthographic systems (Chang, Welbourne & Lee, 2016; Harm & Seidenberg, 2004; Plaut et al. 1996). In this work we show that reading instruction and prior oral language skill also seem to alter the division of labour. This is likely due to the broadly systematic versus arbitrary nature of OP versus OS mappings in English.

In summary, our simulation results have demonstrated that oral language skills mediate the effectiveness of reading instruction in early literacy development. In particular, the beneficial effects of print to sound instruction for reading comprehension depend on high levels of oral vocabulary knowledge. Thus, in line with the Simple View of reading, our modelling work suggests that teaching children about spelling-to-sound mappings needs to be accompanied by substantial training on oral vocabulary, in order to promote reading comprehension. Interventions based on promoting print to sound skills should also ensure effective oral language skills, in order to exploit the benefit of enhancing the regularities available in OP mappings in alphabetic writing systems.

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References

Chang, Y.-N., Welbourne, S., & Lee, C.-Y. (2016). Exploring orthographic neighborhood size effects in a computational model of Chinese character naming. *Cognitive Psychology, 91*, 1-23. doi: http://dx.doi.org/10.1016/j.cogpsych.2016.09.001

Chang, Y.-N., Monaghan, P., & Welbourne, S. (2016). *Effects of experience in a developmental model of reading.* Paper presented at the Proceedings of the 38th Annual Conference of the Cognitive Science Society, Philadelphia.

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: a dual route cascaded model of visual word recognition and reading aloud. *Psychological Review, 108*(1), 204.

Curtis, M. E. (1980). Development of components of reading skill. *Journal of Educational Psychology, 72*(5), 656.

Davis, A. (2013). To read or not to read: decoding Synthetic Phonics. *Impact, 2013*(20), 1-38.

Gough, P. B., & Tunmer, W. E. (1986). Decoding, reading, and reading disability. *Remedial and Special Education,7*(1), 6-10.

Harm, M. W., & Seidenberg, M. S. (2004). Computing the meanings of words in reading: Cooperative division of labor between visual and phonological processes. *Psychological Review, 111*(3), 662-720.

Miller, G. A. (1990). WordNet: An on-line lexical database. *International Journal of Lexicography, 3,* 235-312.

Monaghan, P., Chang, Y.N., Welbourne, S., & Brysbaert, M. (2017). Exploring the relations between word frequency, language exposure, and bilingualism in a computational model of reading. *Journal of Memory and Language, 93*, 1-21.

Nation, K. (2009). Form–meaning links in the development of visual word recognition. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364*(1536), 3665-3674. doi: 10.1098/rstb.2009.0119

Nation, K., & Cocksey, J. (2009). Beginning readers activate semantics from sub-word orthography. *Cognition, 110*(2), 273-278. doi: 10.1016/j.cognition.2008.11.004

Nation, K., & Snowling, M. (2004). Beyond phonological skills: Broader language skills contribute to the development of reading. *Journal of Research in Reading, 27*, 342–356.

Ouellette, G., & Beers, A. (2010). A not-so-simple view of reading: How oral vocabulary and visual-word recognition complicate the story. *Reading and Writing*, *23*, 189-208.

Plaut, D. C., McClelland, J. L., Seidenberg, M. S., & Patterson, K. (1996). Understanding normal and impaired word reading: Computational principles in quasi-regular domains. *Psychological Review, 103*(1), 56-115.

Rayner, K., Foorman, B. R., Perfetti, C. A., Pesetsky, D., & Seidenberg, M. S. (2001). How psychological science informs the teaching of reading. *Psychological science in the Public Interest, 2*(2), 31-74.

Ricketts, J., Nation, K., & Bishop, D. (2007). Vocabulary is important for some, but not all reading skills. *Scientific Studies of Reading, 11*, 235–257.

Seidenberg, M. (2017). *Language at the speed of sight: How we read, why so many can't, and what can be done about it.* New York: Basic Books.

Seidenberg, M. S., & McClelland, J. L. (1989). A distributed, developmental model of word recognition and naming. *Psychological Review, 96*(4), 523-568.

Taylor, J. S. H., Davis, M. H., & Rastle, K. (2017). Comparing and validating methods of reading instruction using behavioural and neural findings in an artificial orthography. *Journal of Experimental Psychology: General.* Advance online publication.

Taylor, J.S.H., Duff, F.J., Woollams, A., Monaghan, P., & Ricketts, J. (2015). How word meaning influences word reading. *Current Directions in Psychological Science, 24*, 322-238.